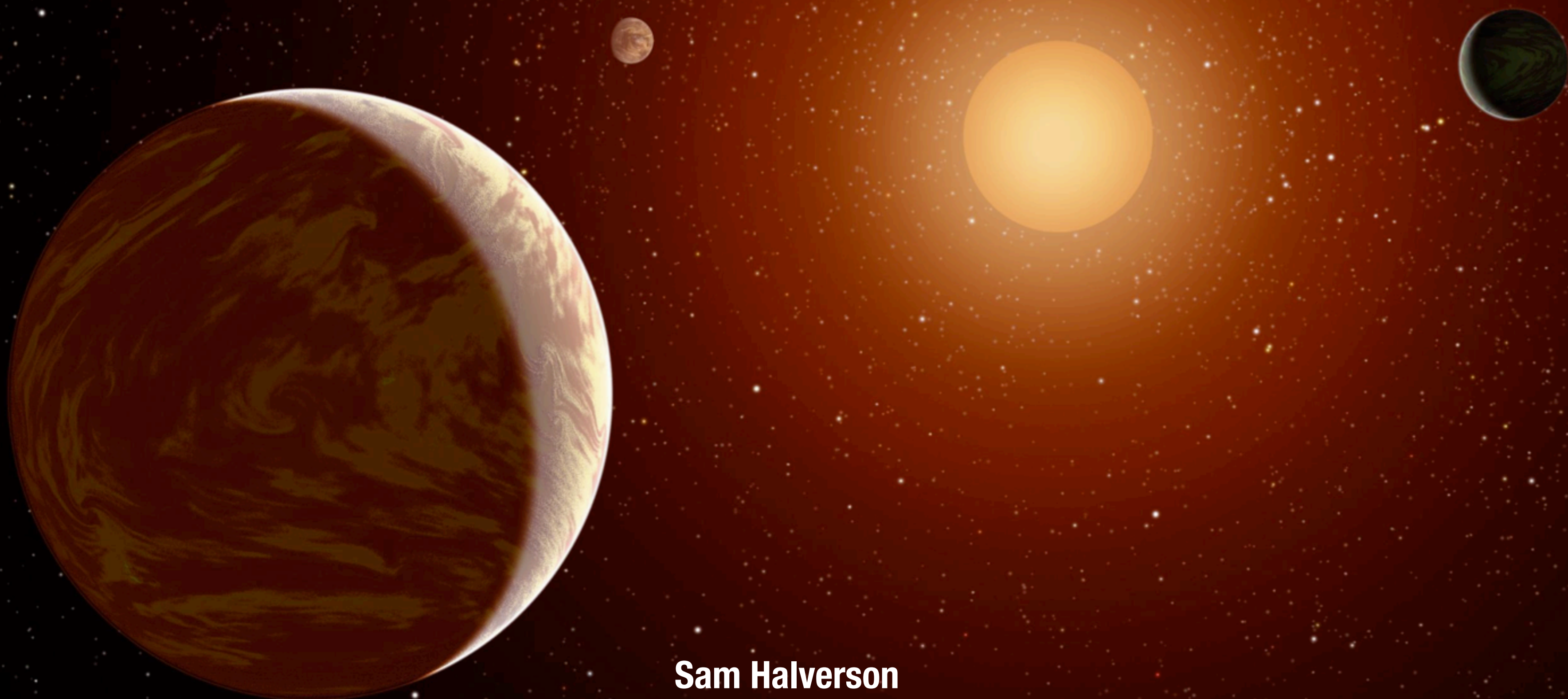
Next-generation planet hunters in the optical and near-Infrared



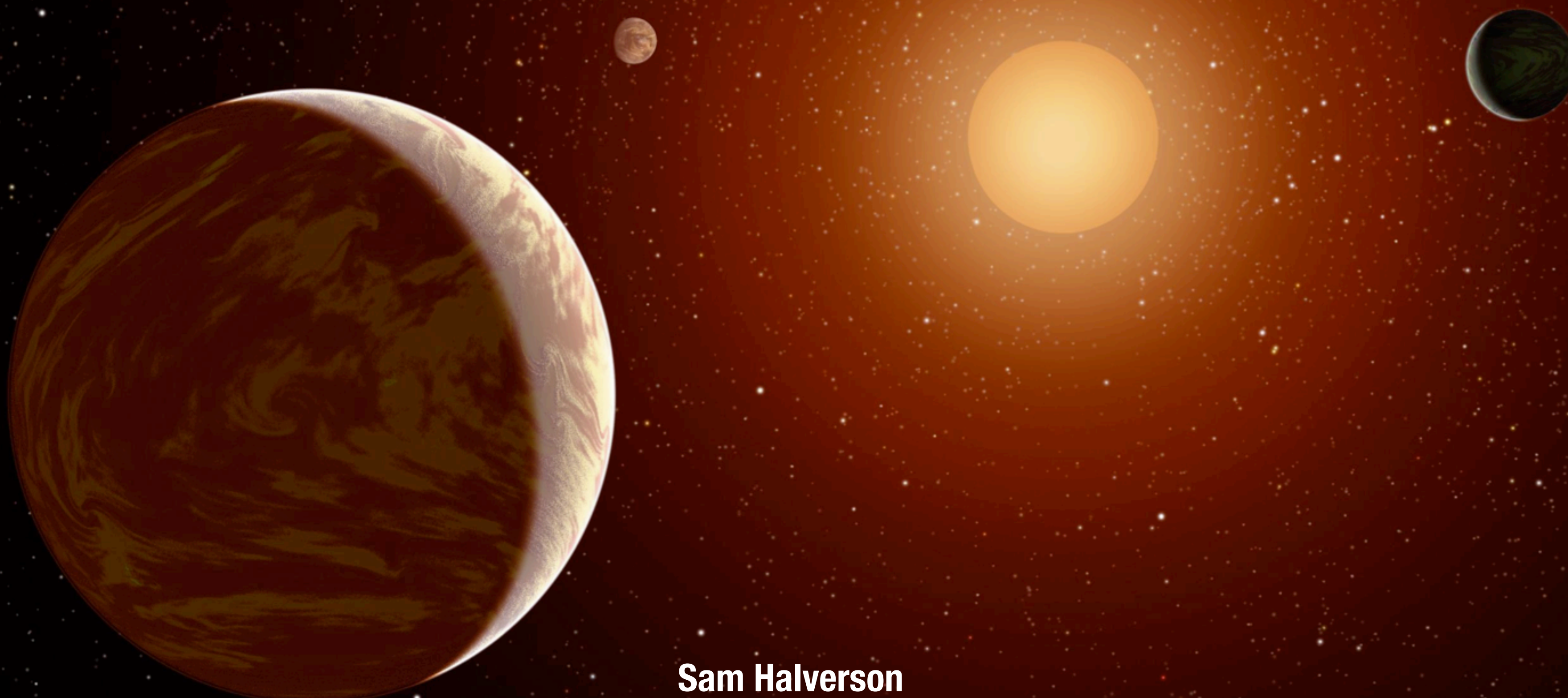
Sam Halverson

University of Pennsylvania

Image credit: NASA/JPL

Next-generation ~~planet hunters~~ in the optical and near-Infrared

Doppler spectrometers



Sam Halverson
University of Pennsylvania

Image credit: NASA/JPL

Next-generation ~~planet hunters~~ in the optical and near-Infrared

stellar activity measurement machines

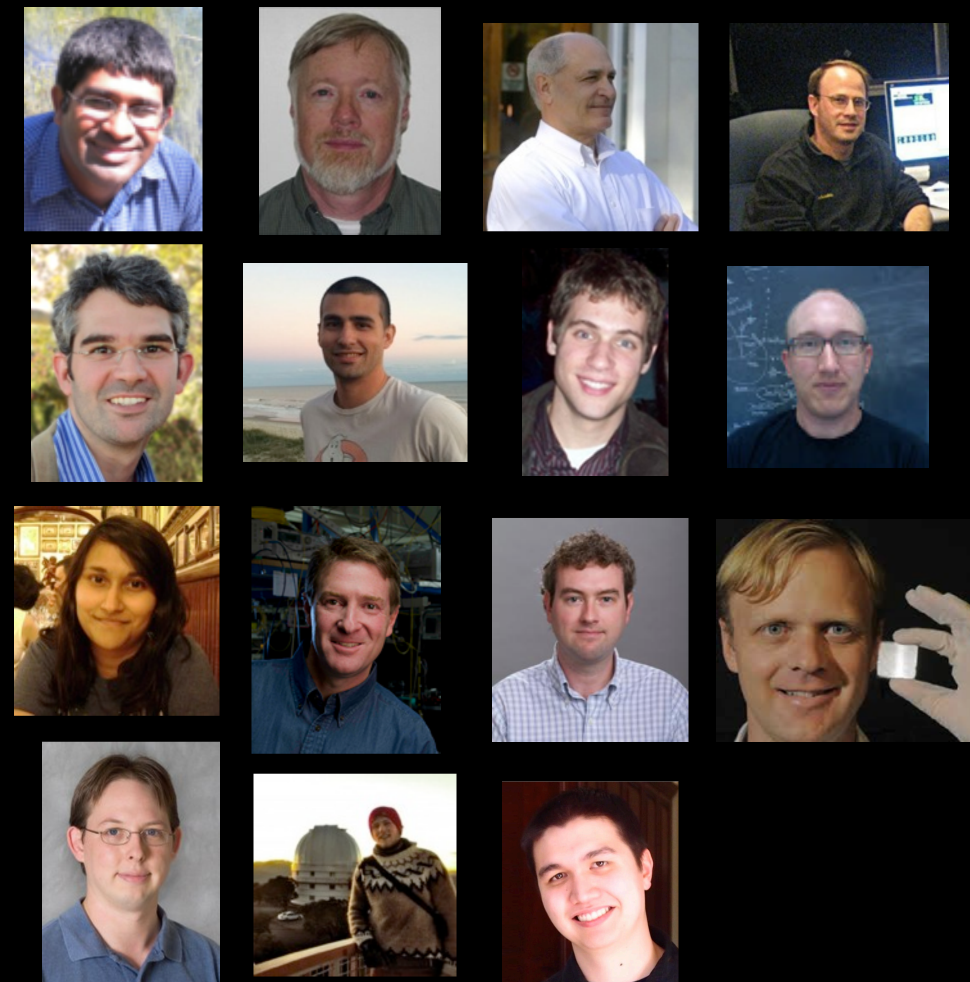
Sam Halverson

University of Pennsylvania

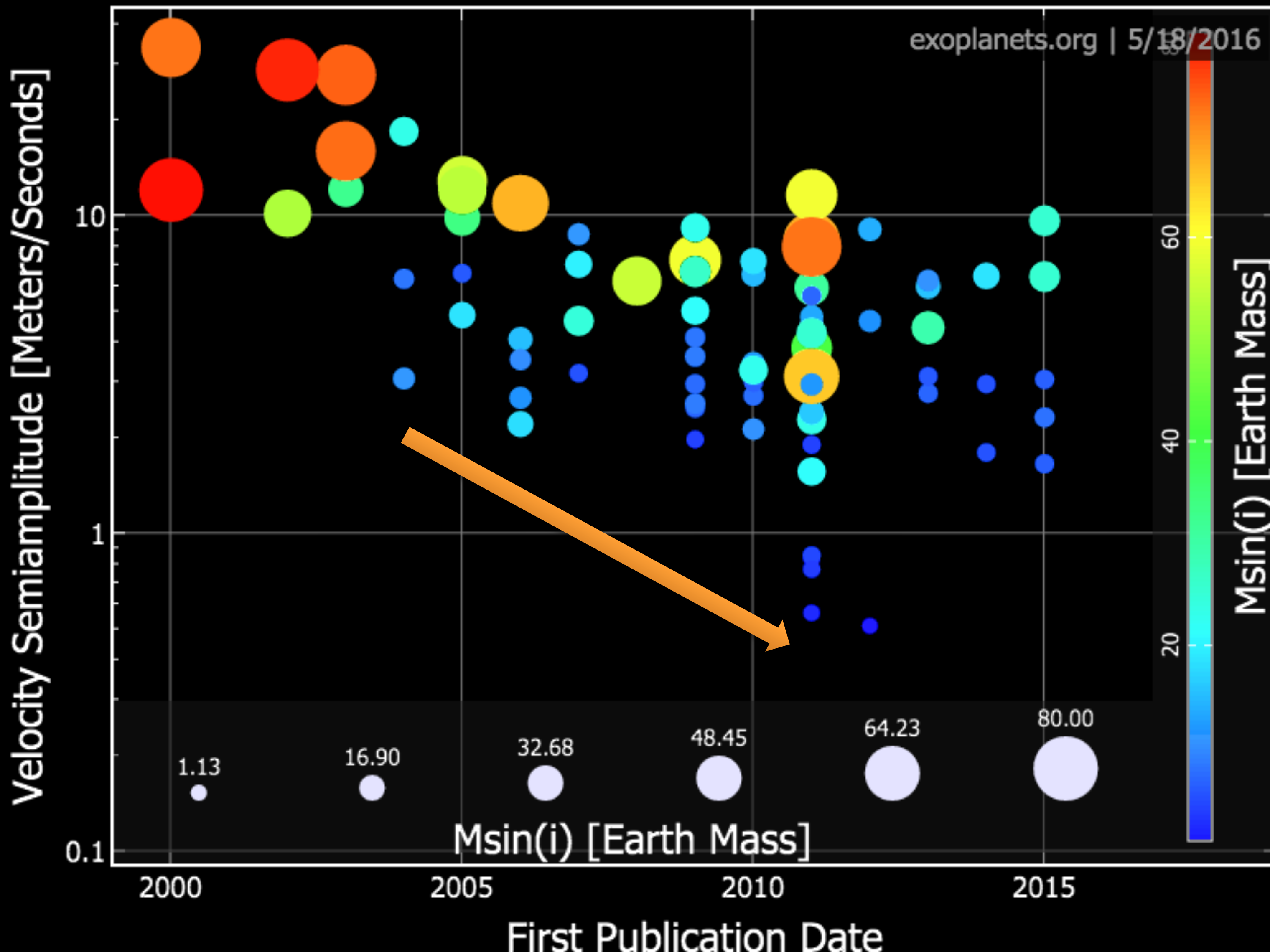
Image credit: NASA/JPL

Full collaboration snapshot

- Suvrath Mahadevan (PSU - PI)
- Larry Ramsey (PSU)
- Fred Hearty (PSU)
- Sam Halverson (Penn)
- Chad Bender (UA)
- Chris Schwab (Macquarie)
- Paul Robertson (PSU)
- Andy Monson (PSU)
- Jason Wright (PSU)
- Tyler Anderson (PSU)
- Scott Diddams (NIST Boulder)
- Ryan Terrien (NIST Boulder)
- Cullen Blake (Penn)
- Mike McElwain (GSFC)
- Qian Gong (GSFC)
- Arpita Roy (Caltech)
- Gudmundur Stefansson (PSU)

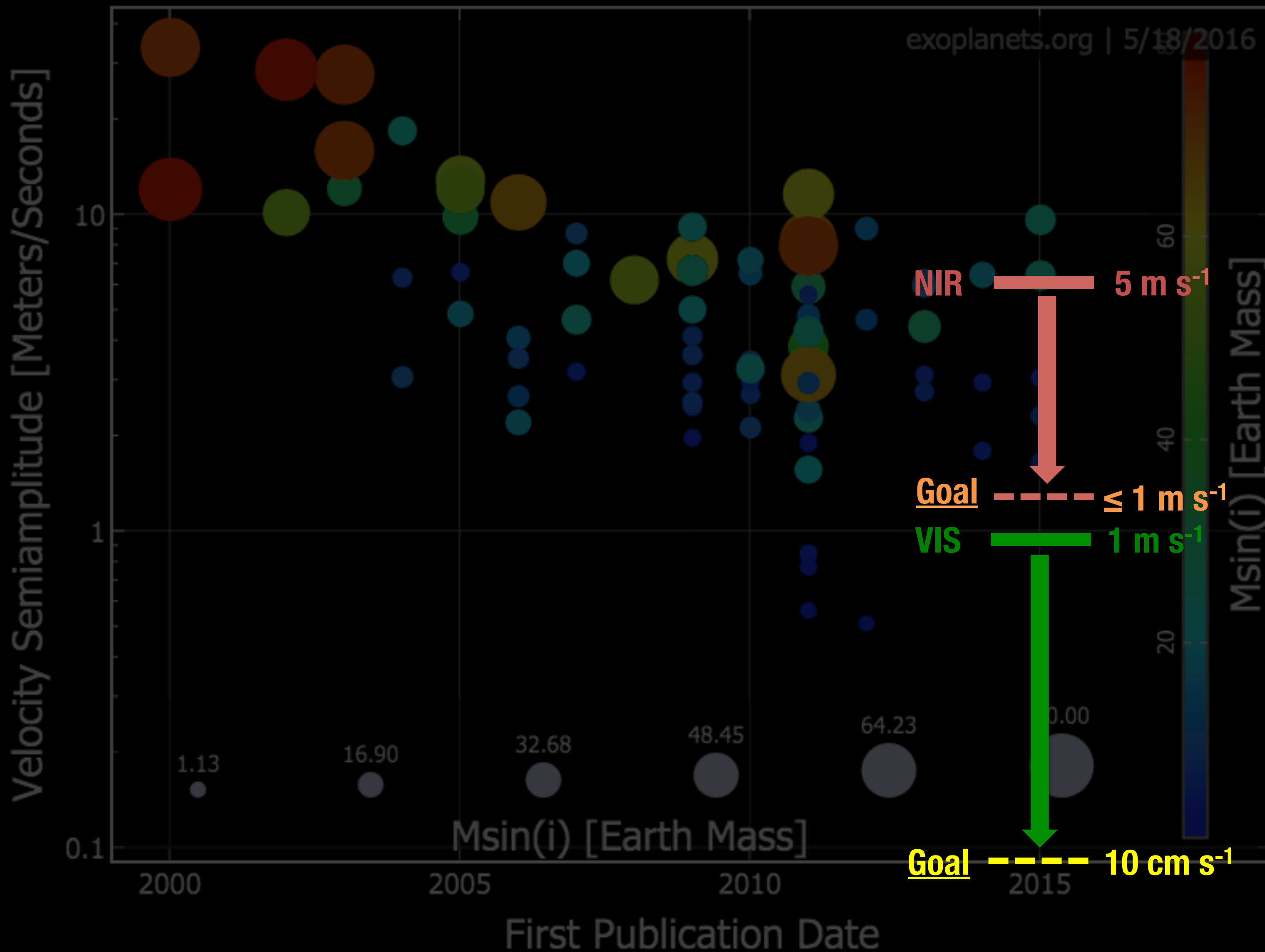


Radial velocity planet discovery space

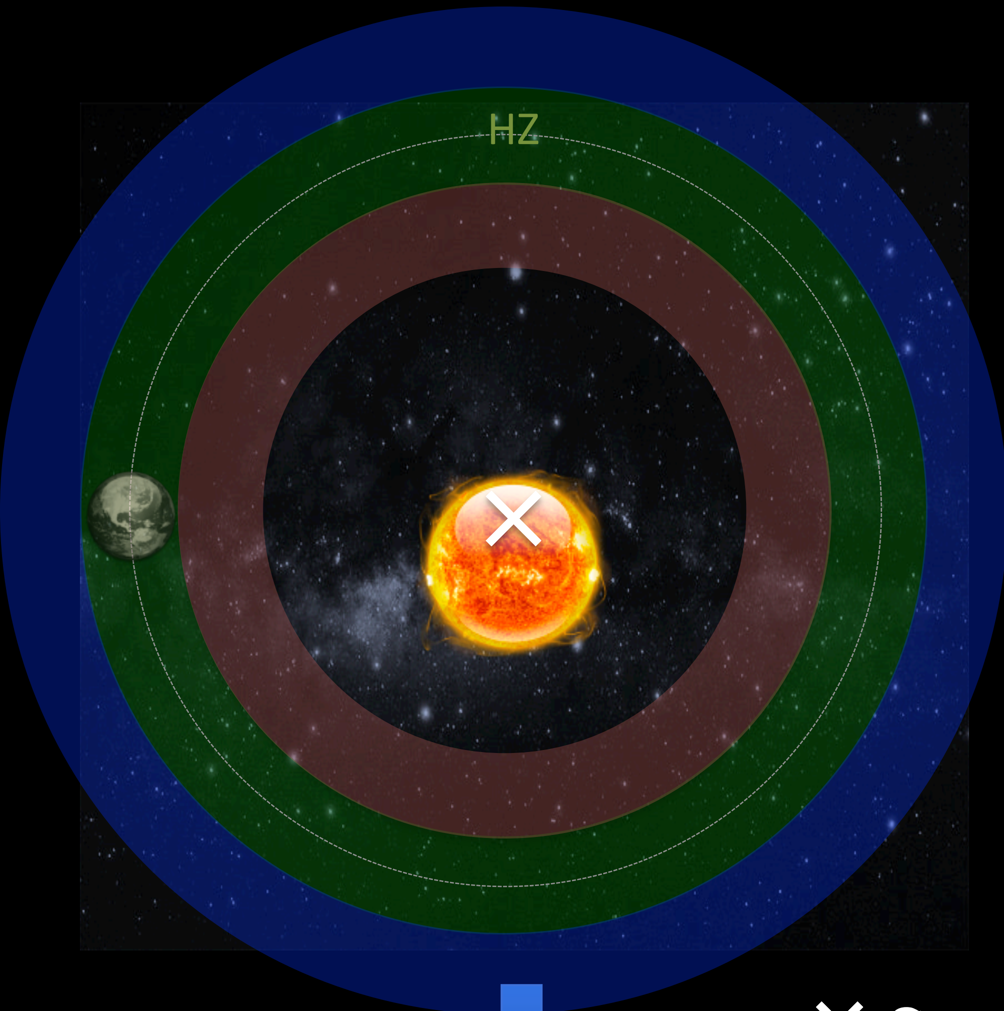


RV signal induced by Earth

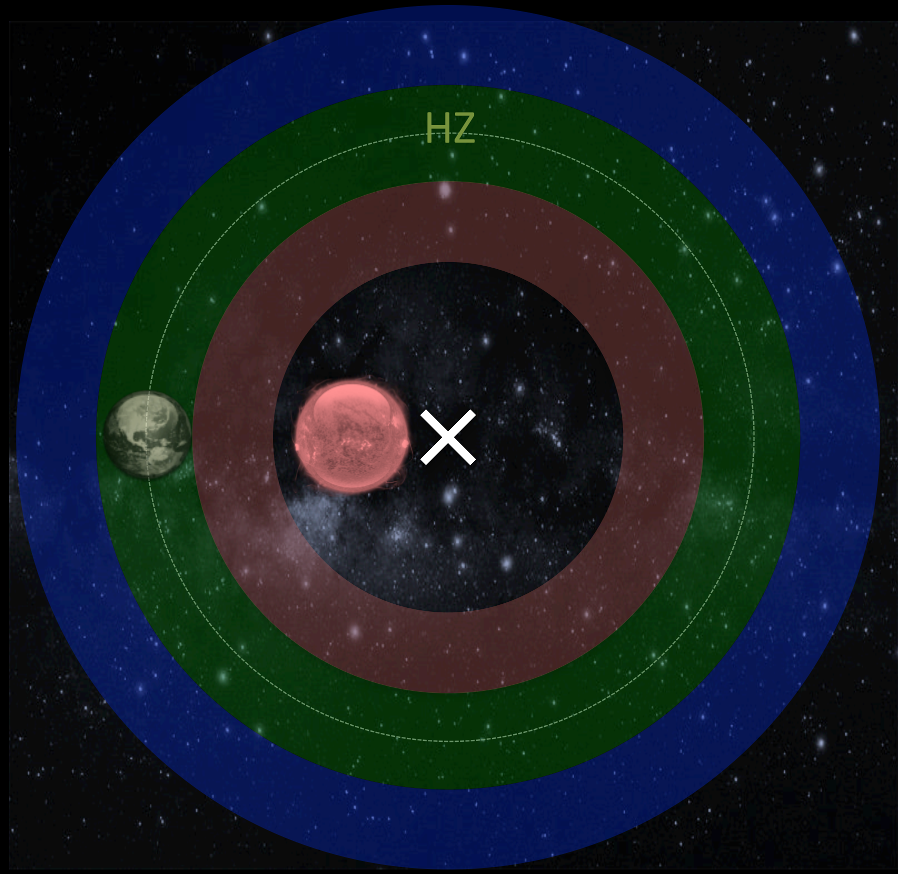
Current instrumental state of the art in precision Doppler spectroscopy



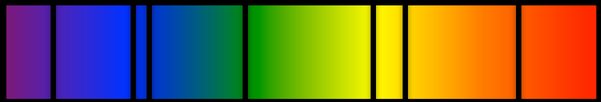
Sun-like System



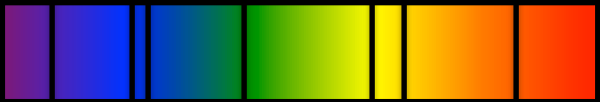
M-Dwarf System



X: Center of Mass



~10 cm/s



~1 m/s

Pushing towards Earth-mass planets will require a shift in technologies

<u>Earth-size planets in the Habitable-zone</u>

Shift focus to M-dwarfs

Larger Doppler signals

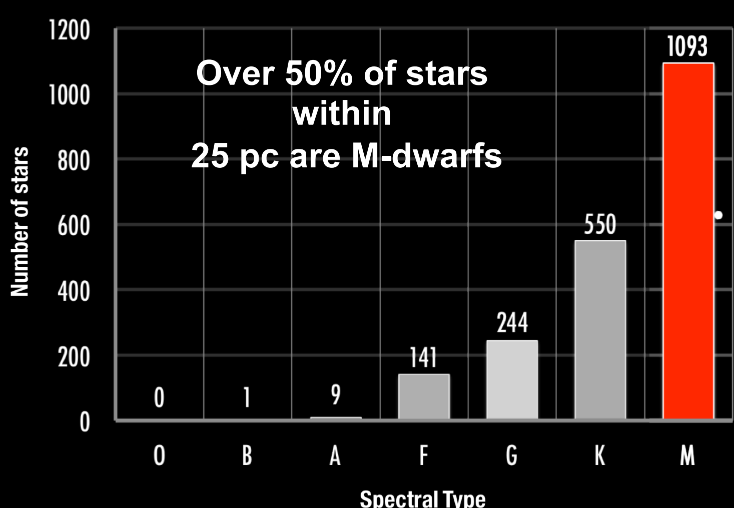
NIR spectrometers

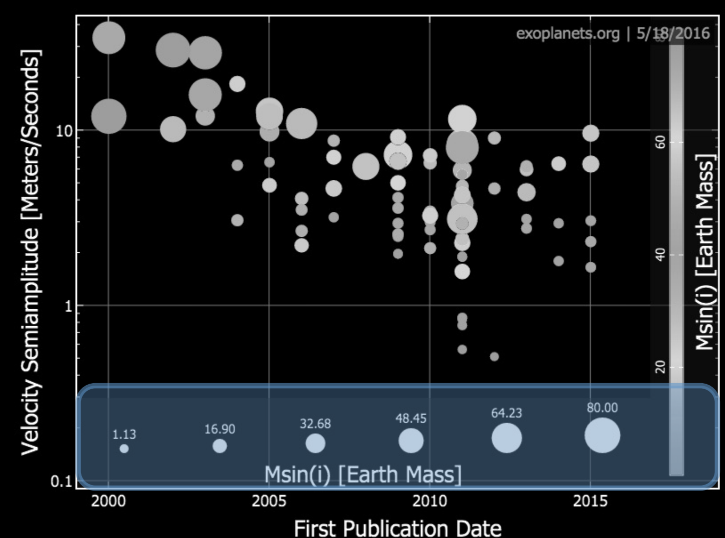
Improve measurement precisions in the optical

Improved spectrometer design

Optical frequency combs

Dedicated telescope time





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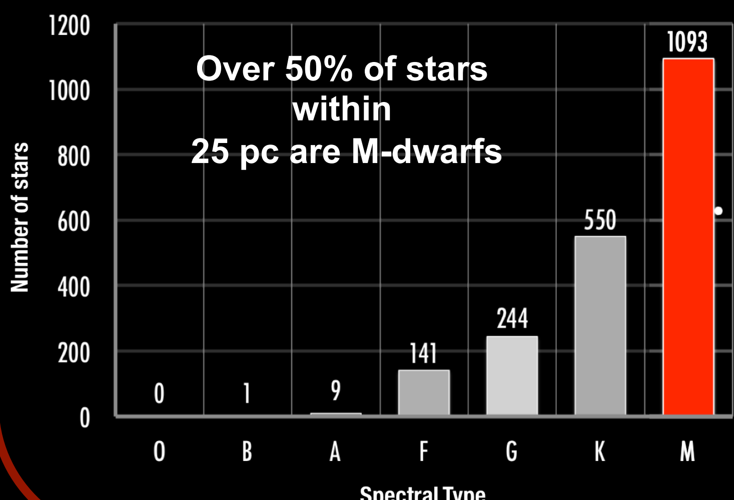

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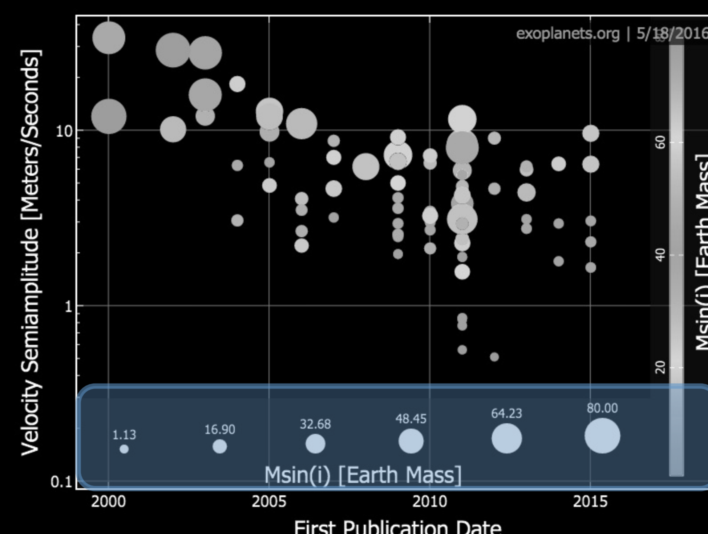
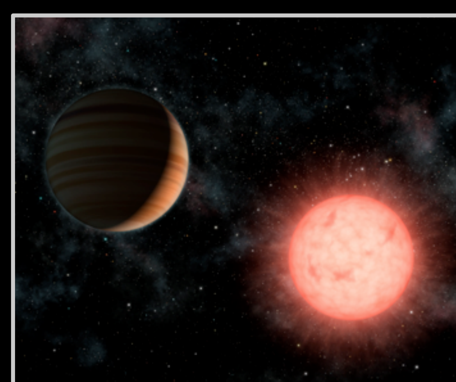


The Habitable-zone Planet Finder (HPF) instrument

Near-infrared spectrometer

10 meter telescope

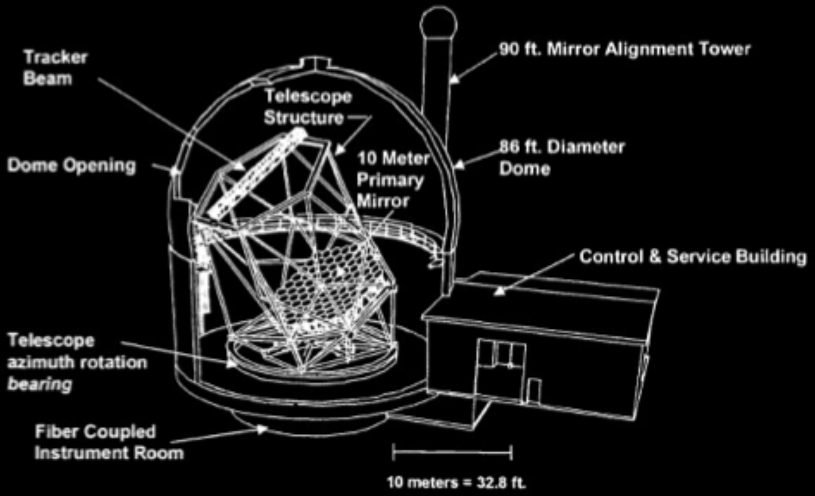


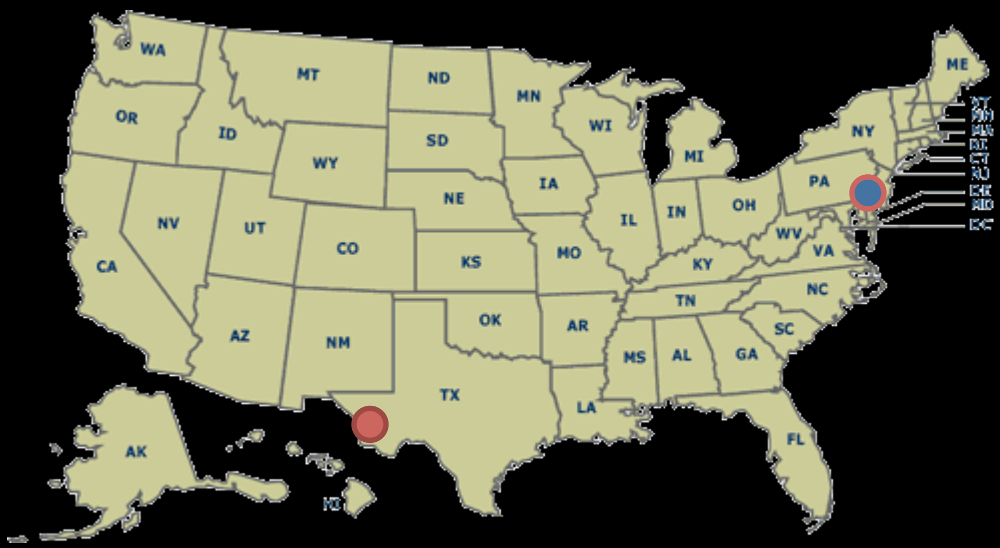
NSF MRI funded, Fall 2011

http://hpf.psu.edu/

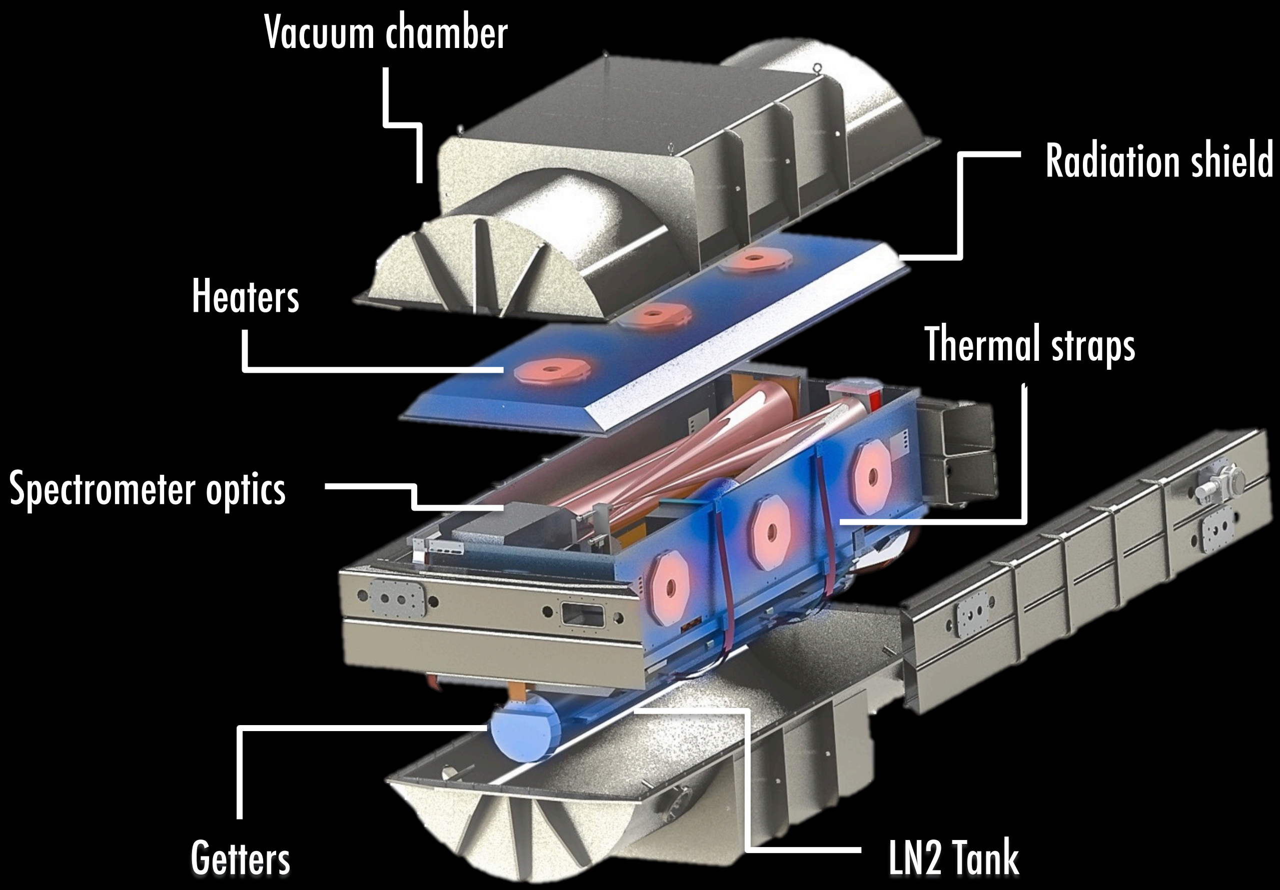
The Hobby-Eberly Telescope

- Located at McDonald Observatory
- 10 meter effective aperture
- *Fixed zenith angle design.*
- University partners: UT Austin, PSU, Stanford, Munich, Gottingen
- **Queue-based observing**



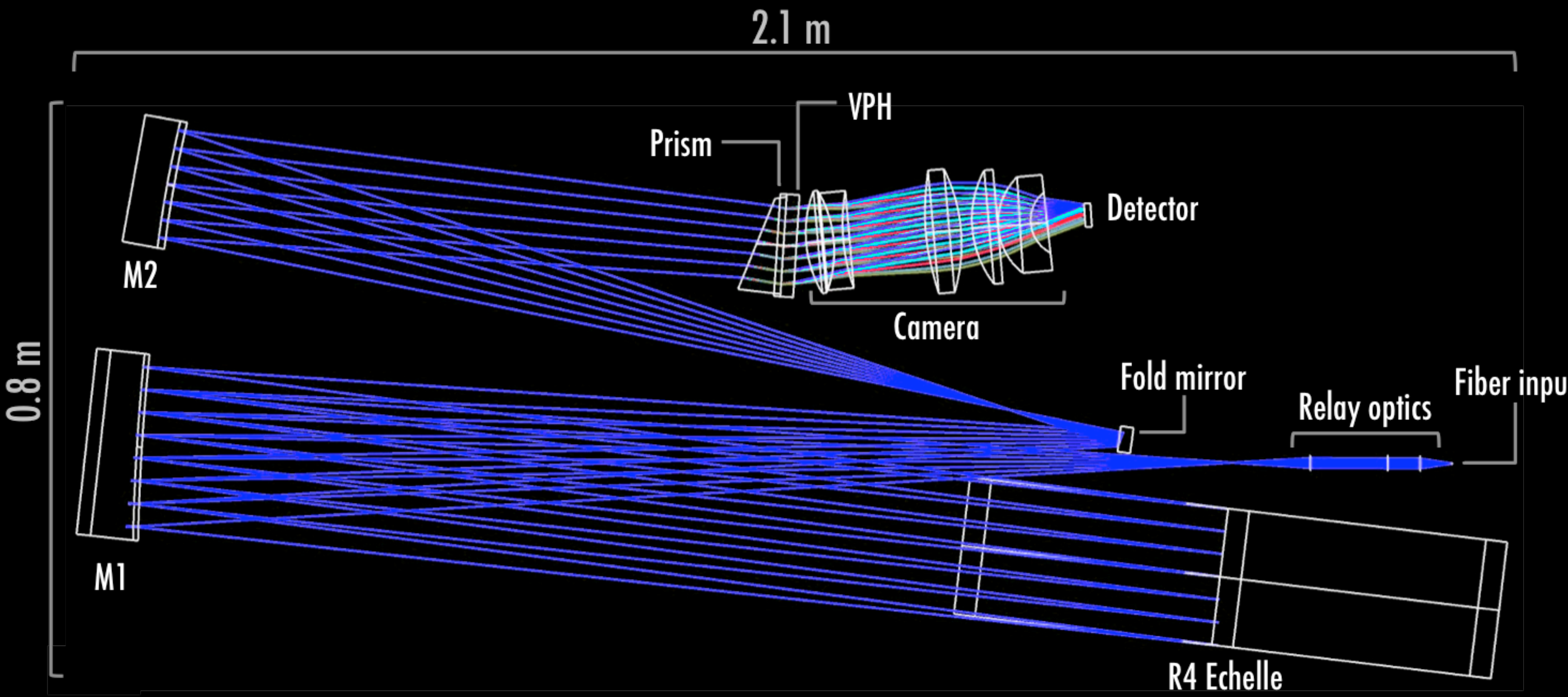


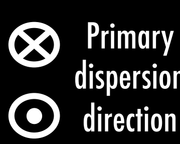
The Habitable-zone Planet Finder Spectrometer



- Near-infrared coverage (800 – 1300 nm)
- Cryogenic operation (180 K), *0.1 mK thermal stability achieved*
- Fed by custom optical fiber delivery system, **optical frequency comb calibration source**
- *<1 m/s single measurement precision goal (**J<10, 30 min**)*
- ***Q3 2017 delivery***

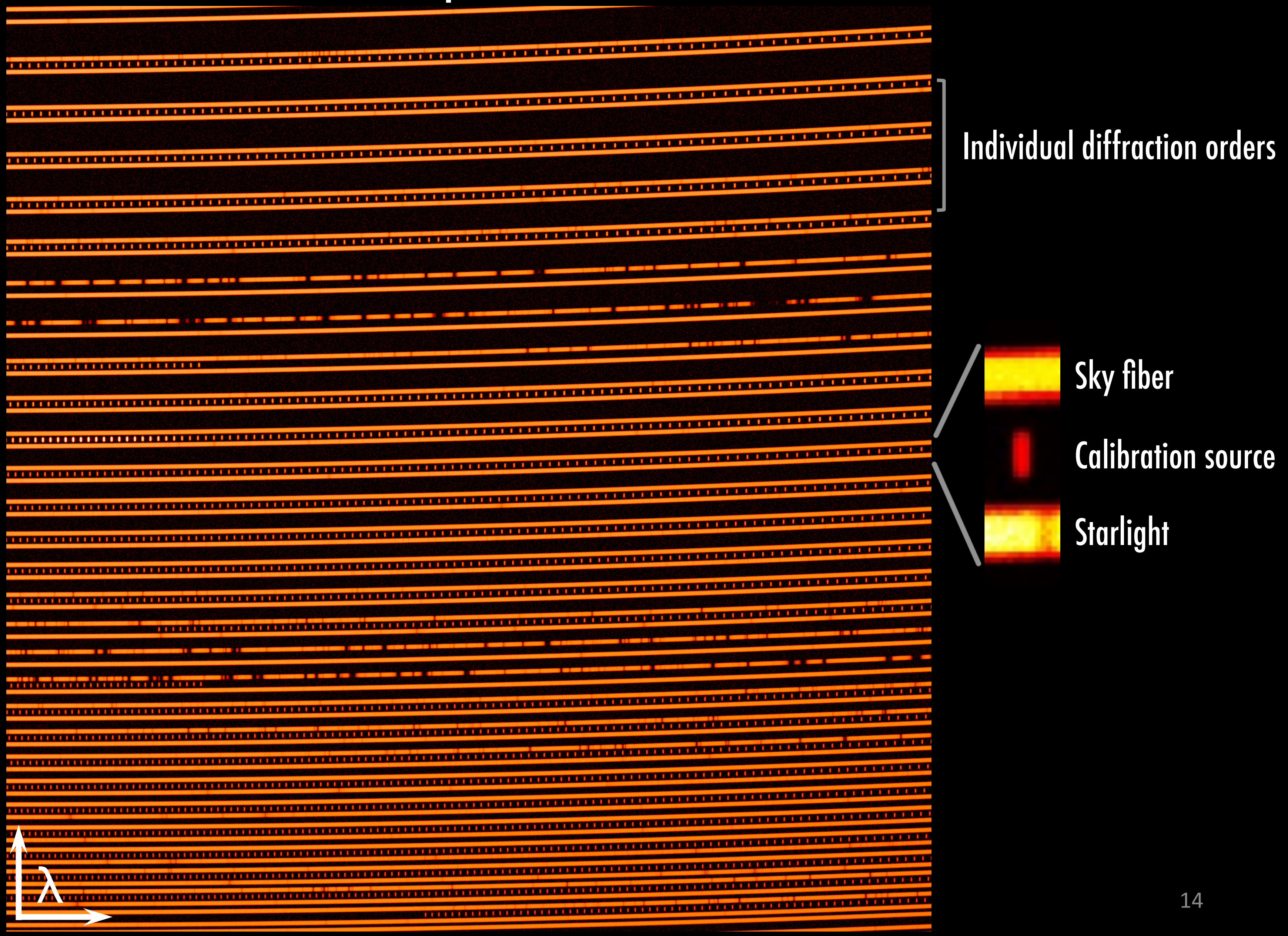
HPF optical train





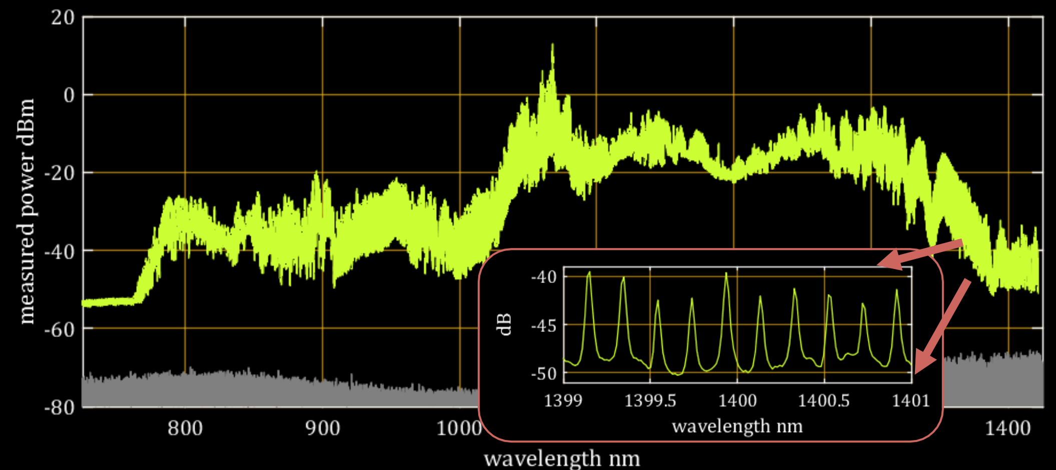
- Asymmetric white-pupil design.
- R4 echelle grating for primary dispersion, VPH grism for cross-dispersion
- R = 50,000, z/Y/J band coverage (800 – 1300 nm), 1.5” fiber w/ 0.5” slit
- **1.7 micron cutoff Hawaii-2RG detector**

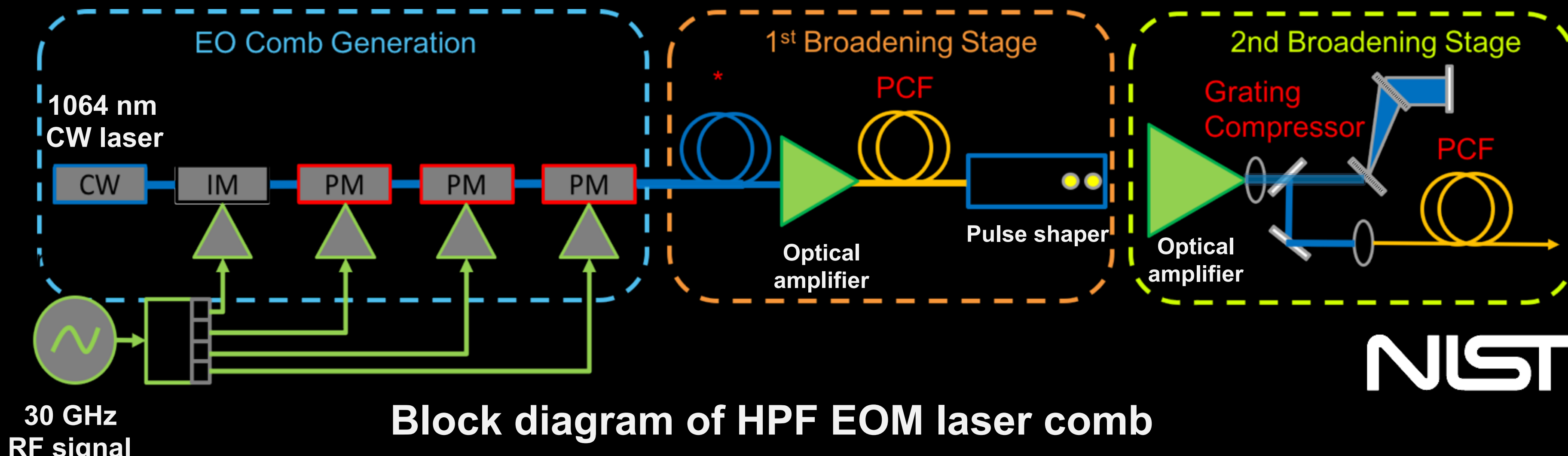
Simulated HPF focal plane on H2RG detector



Primary calibration source is broadband laser frequency comb

- Picket fence of lines tied to atomic standard.
- Stable at the <1 *cm s*$^{-1}$ level.
- *HPF will use broadband electro-optic comb for primary calibration*

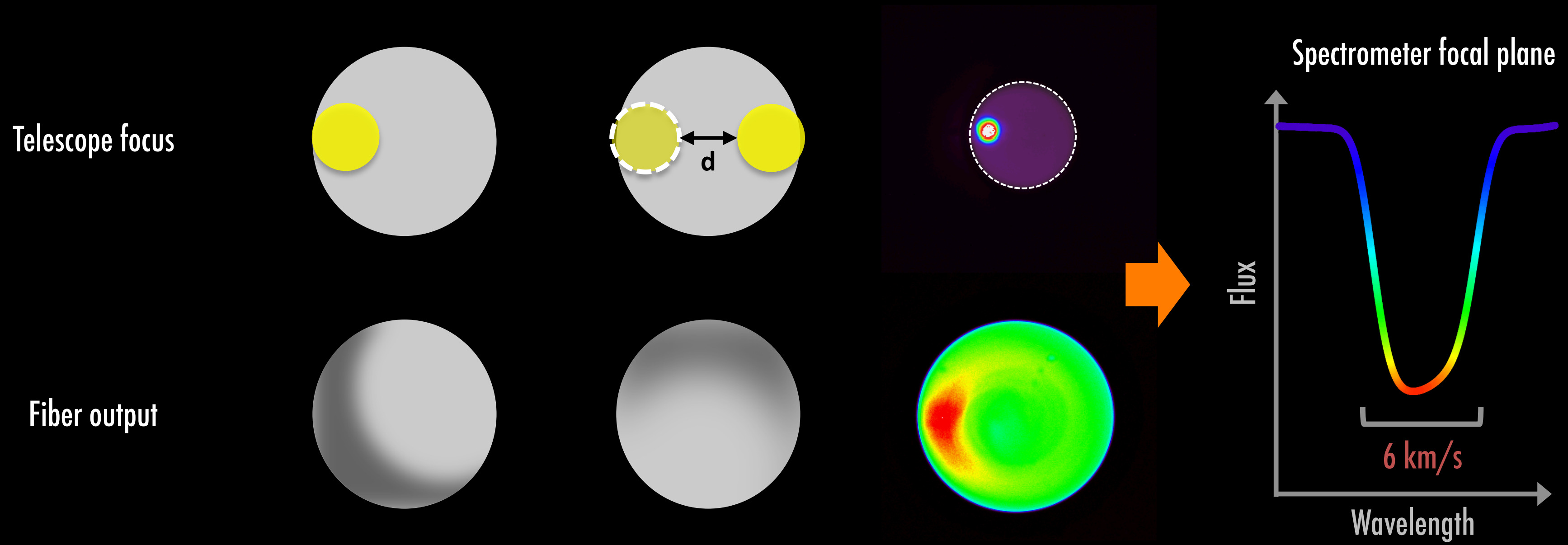




Block diagram of HPF EOM laser comb

lide credit: AJ Metcalf, NIST Boulder

Illumination stability is critical



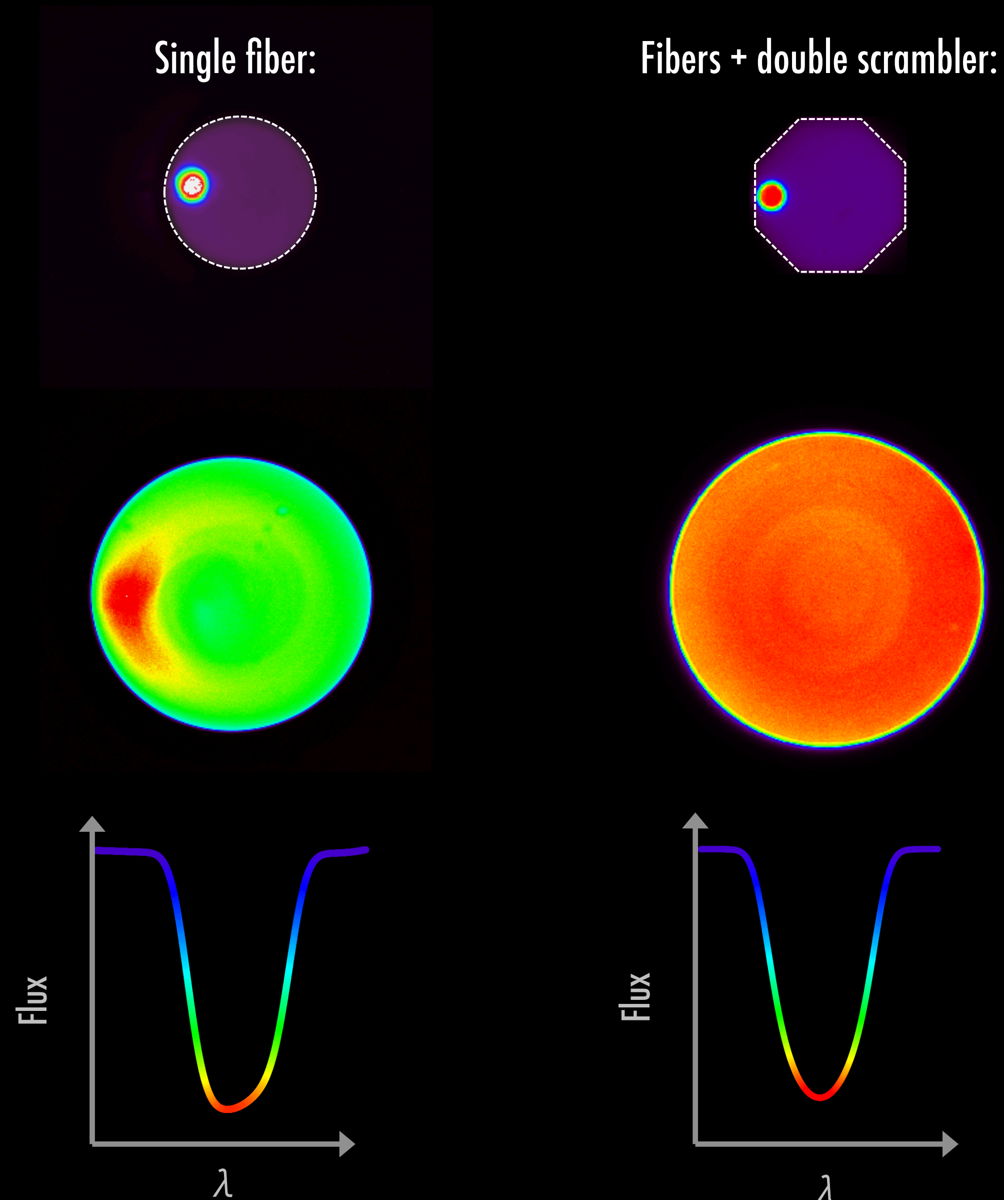
- Fundamentally, *spectrometer records monochromatic images of fiber face*
  - Guiding errors and telescope pupil changes manifest as spectral line changes*
- *Not* traced with calibration source

Specialty fibers essential for stabilizing spectrometer PSF

Telescope focal plane

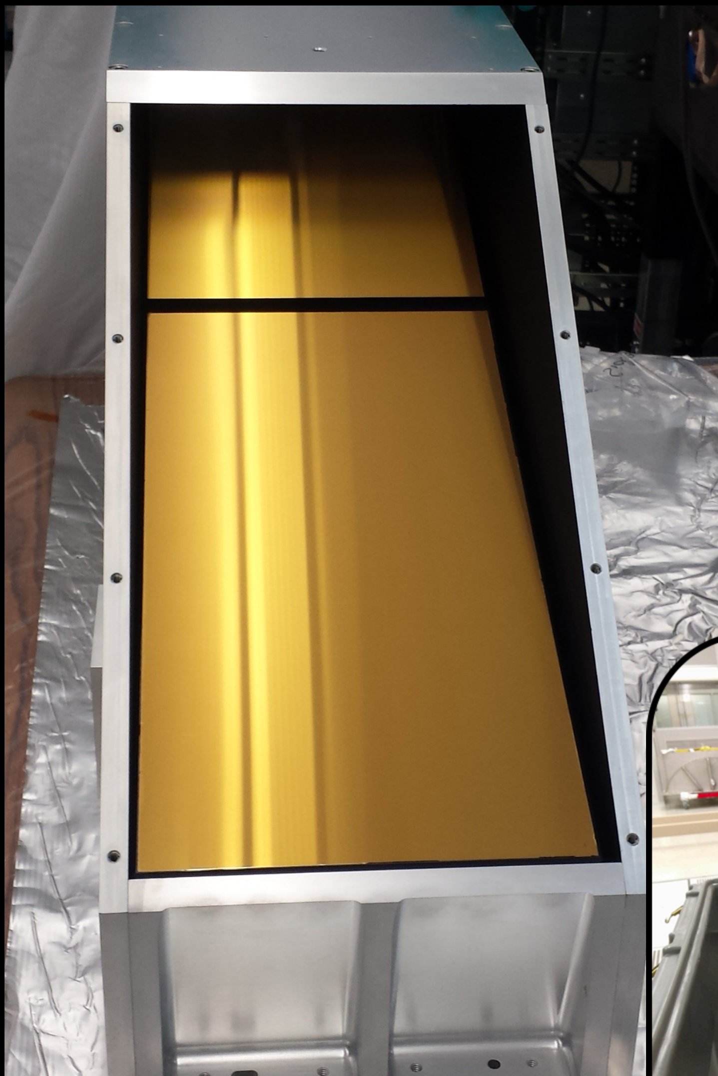
Fiber output

Instrument profile
(spectral line)

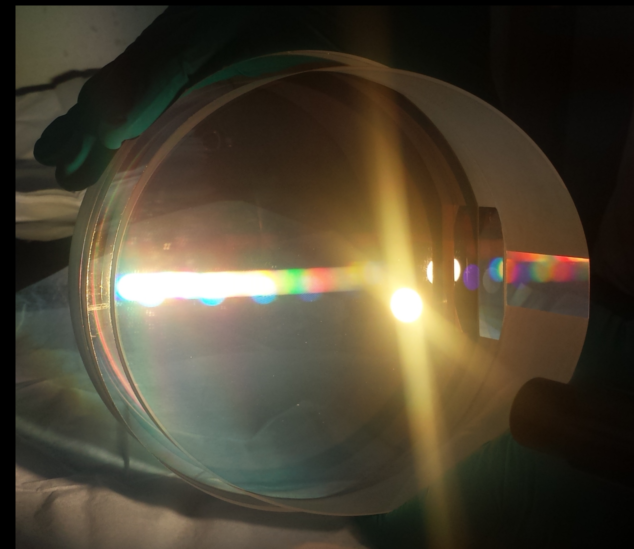


Optic integration complete

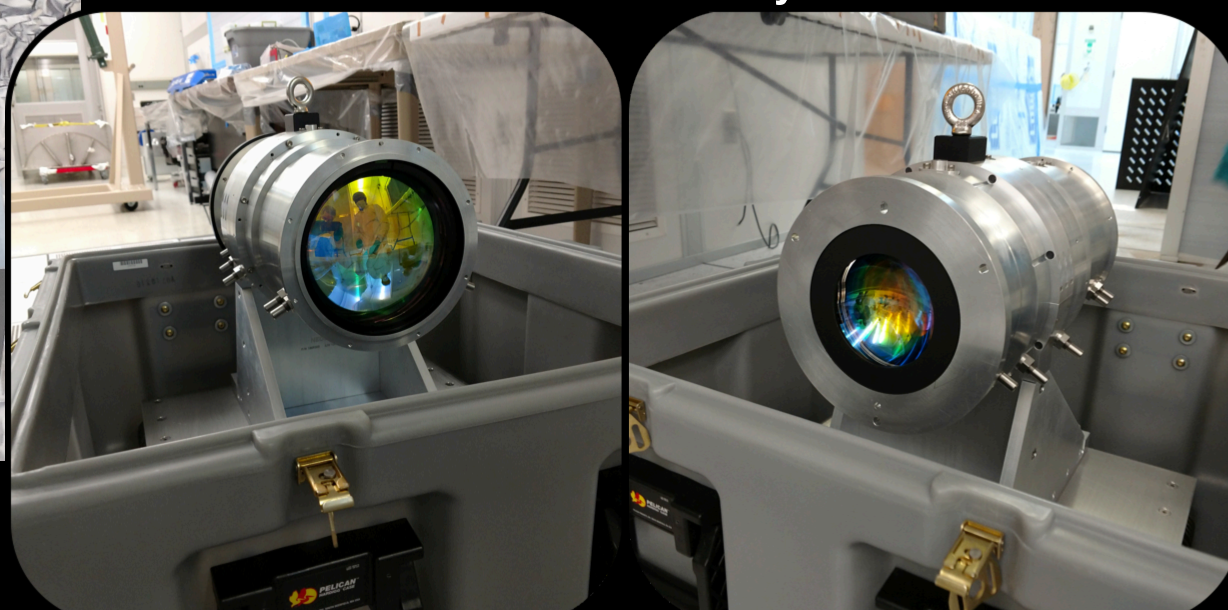
Echelle grating



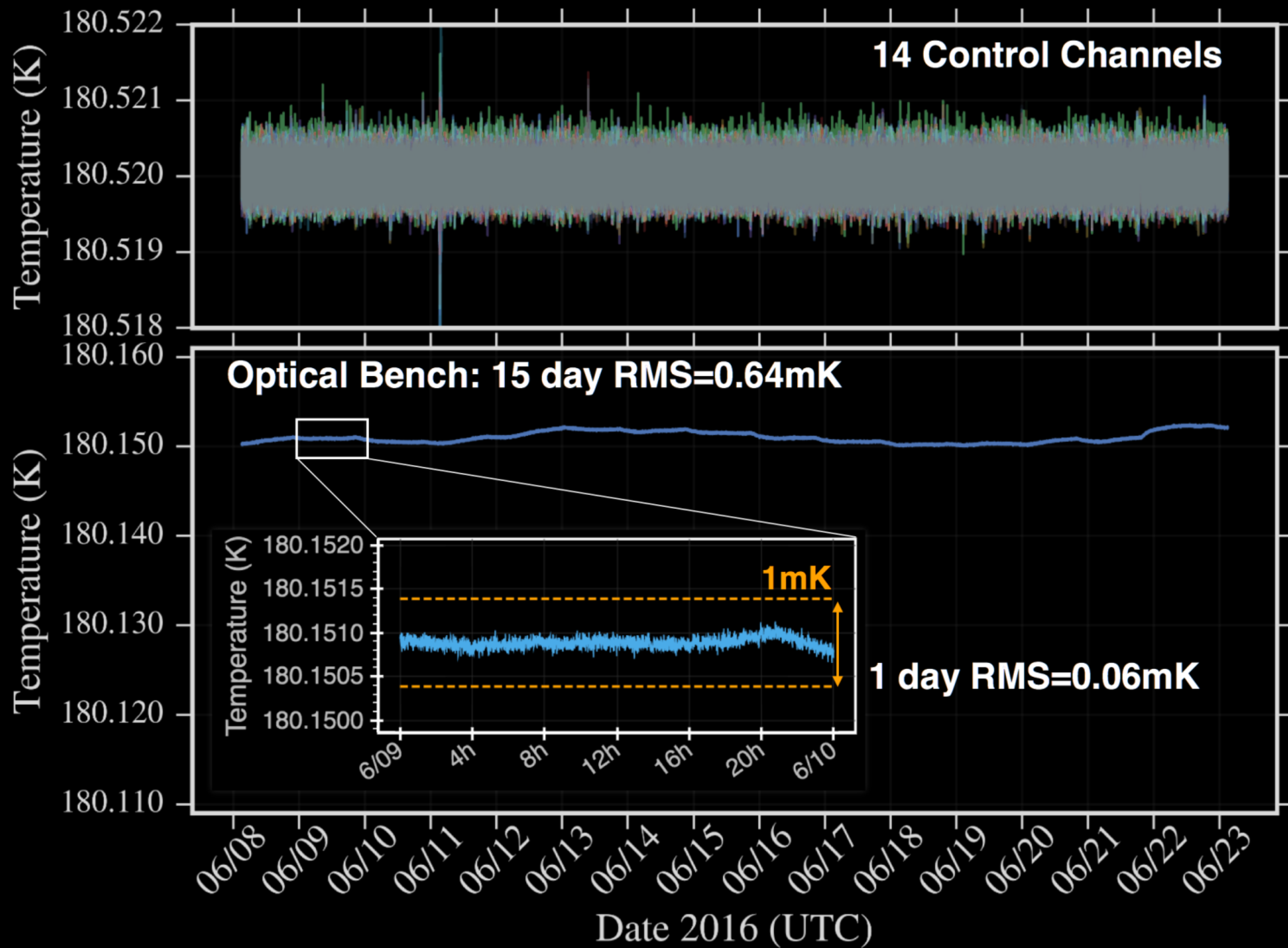
VPH grism



Camera assembly

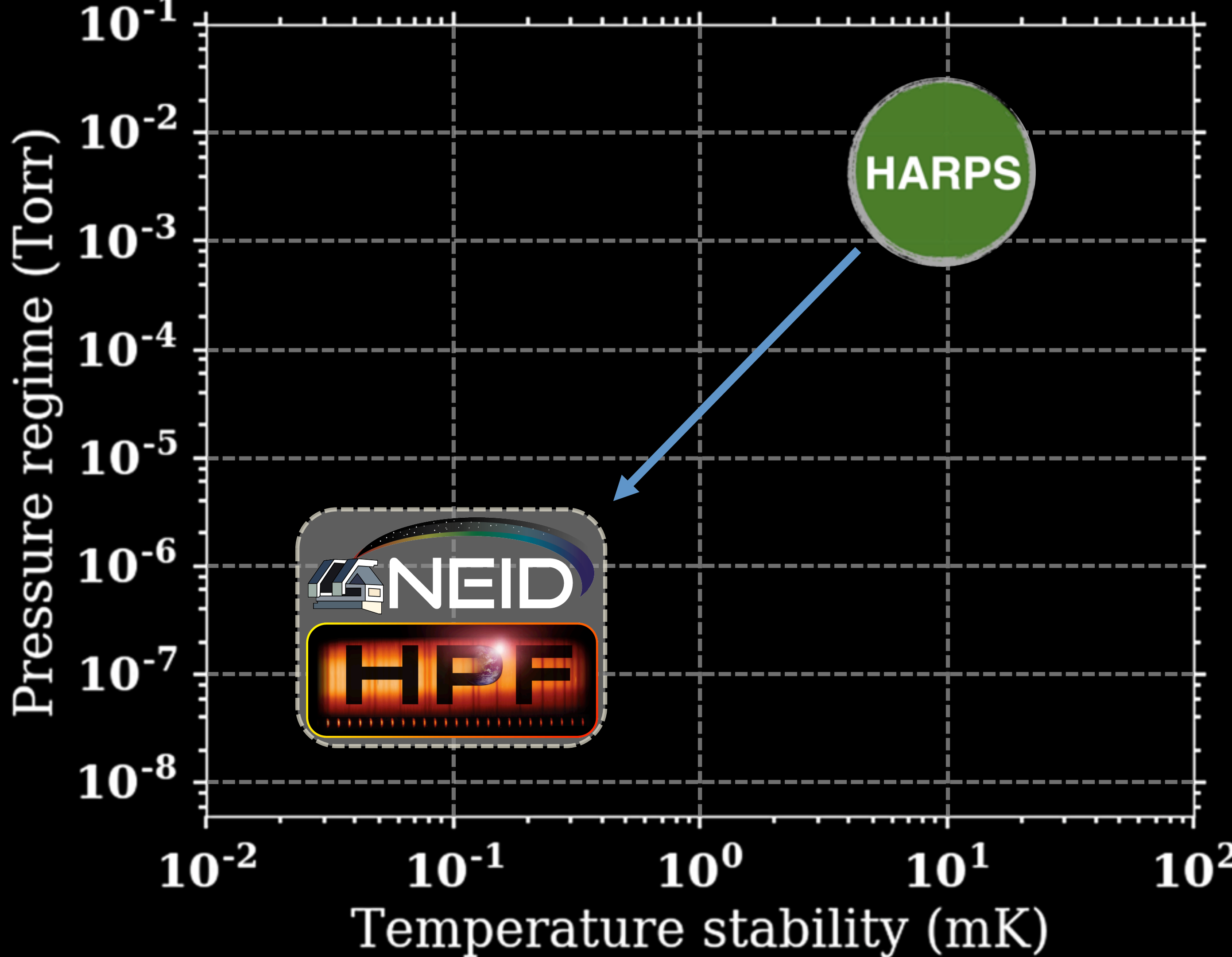


Thermal control stability within cryostat

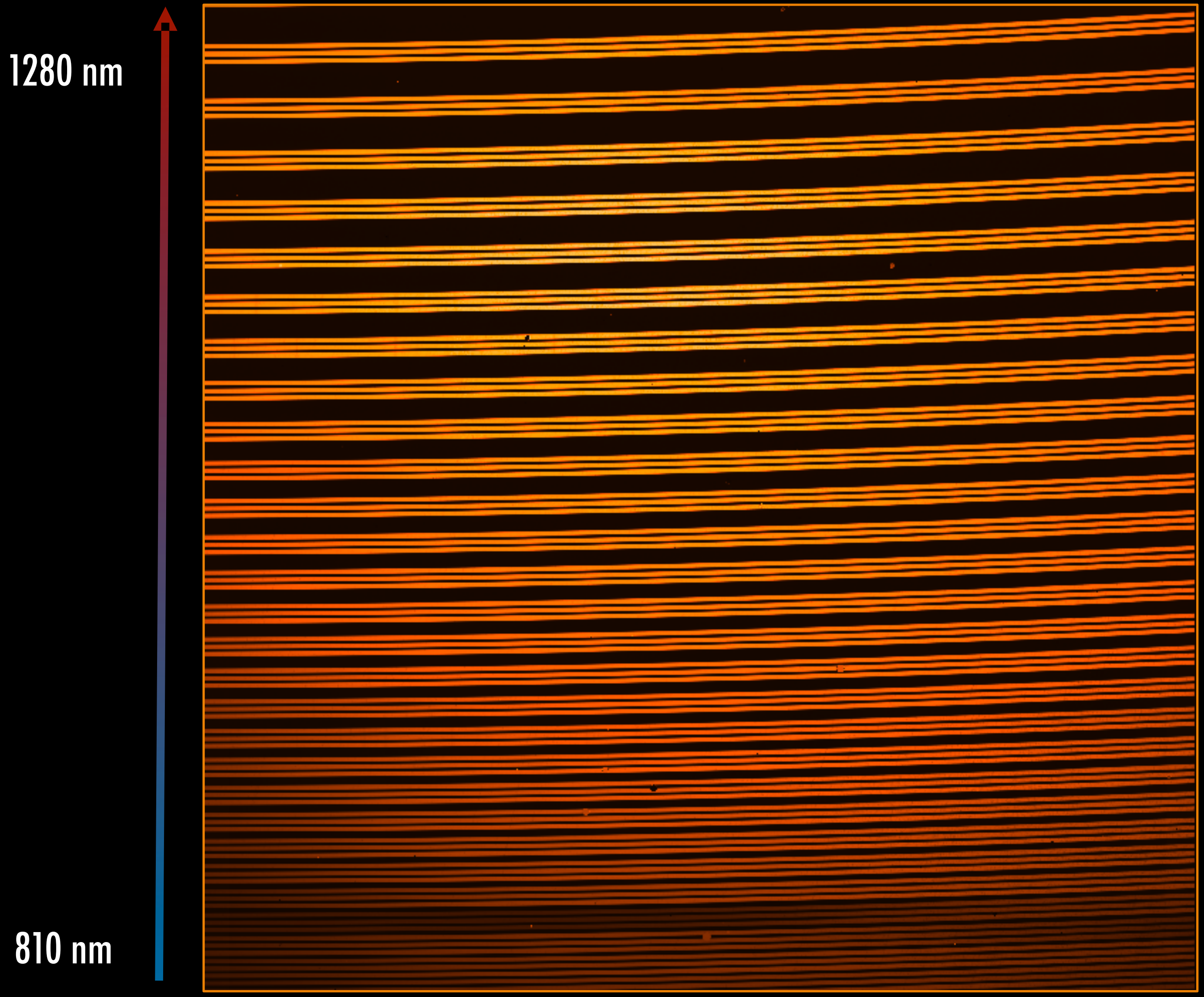


Robertson+ 2016

Environmental control precision



First light laboratory image



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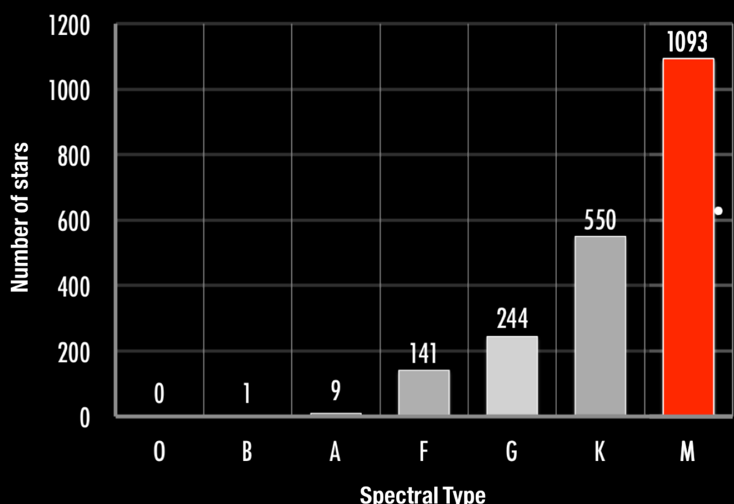
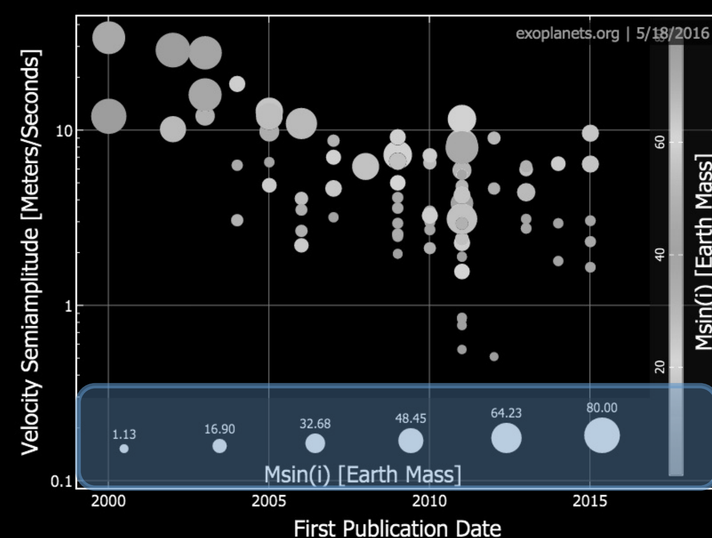
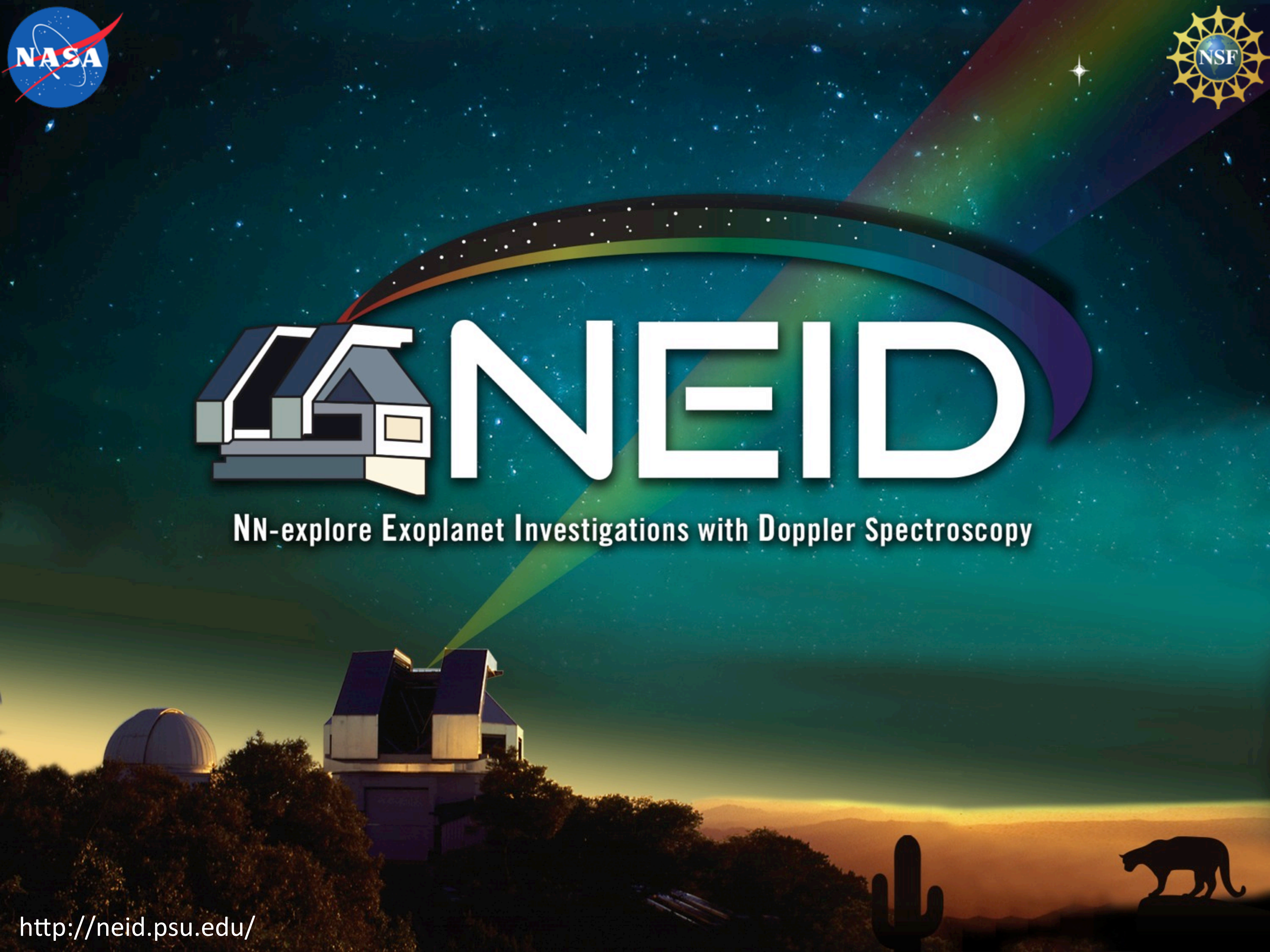
NIR spectrometers



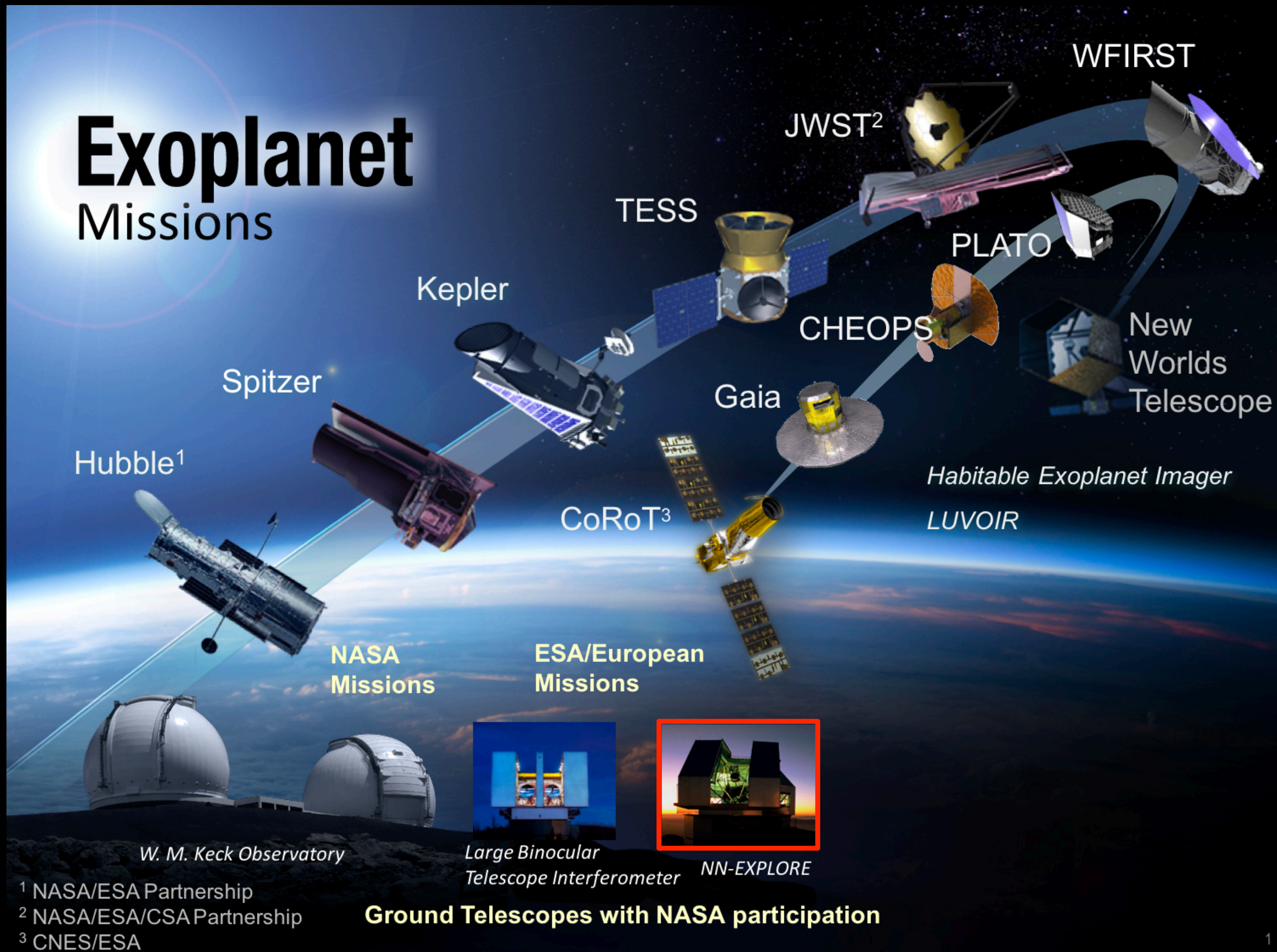
Improve measurement precisions in the optical

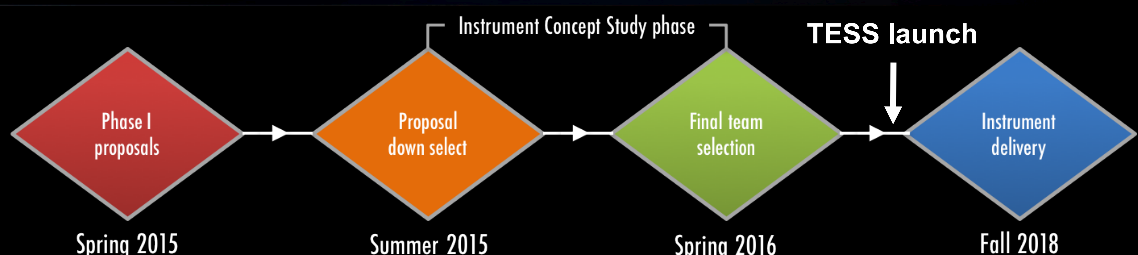
Improved spectrometer design
Optical frequency combs
Dedicated telescope time




NASA
NSF
NEID
NN-explore Exoplanet Investigations with Doppler Spectroscopy
http://neid.psu.edu/

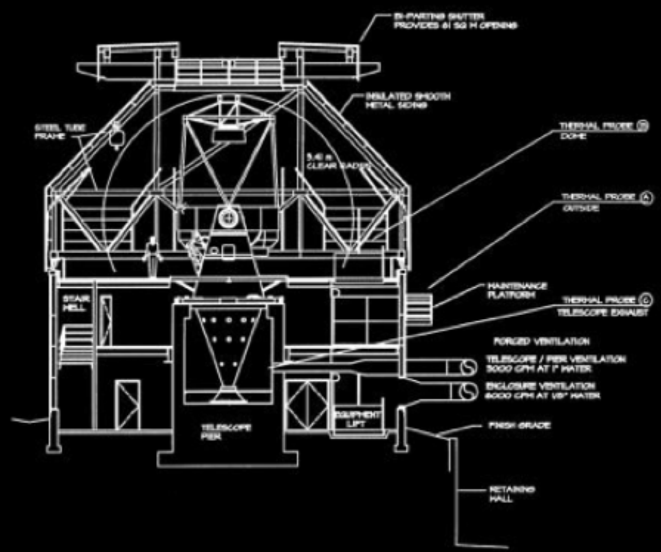
NASA Exoplanet roadmap





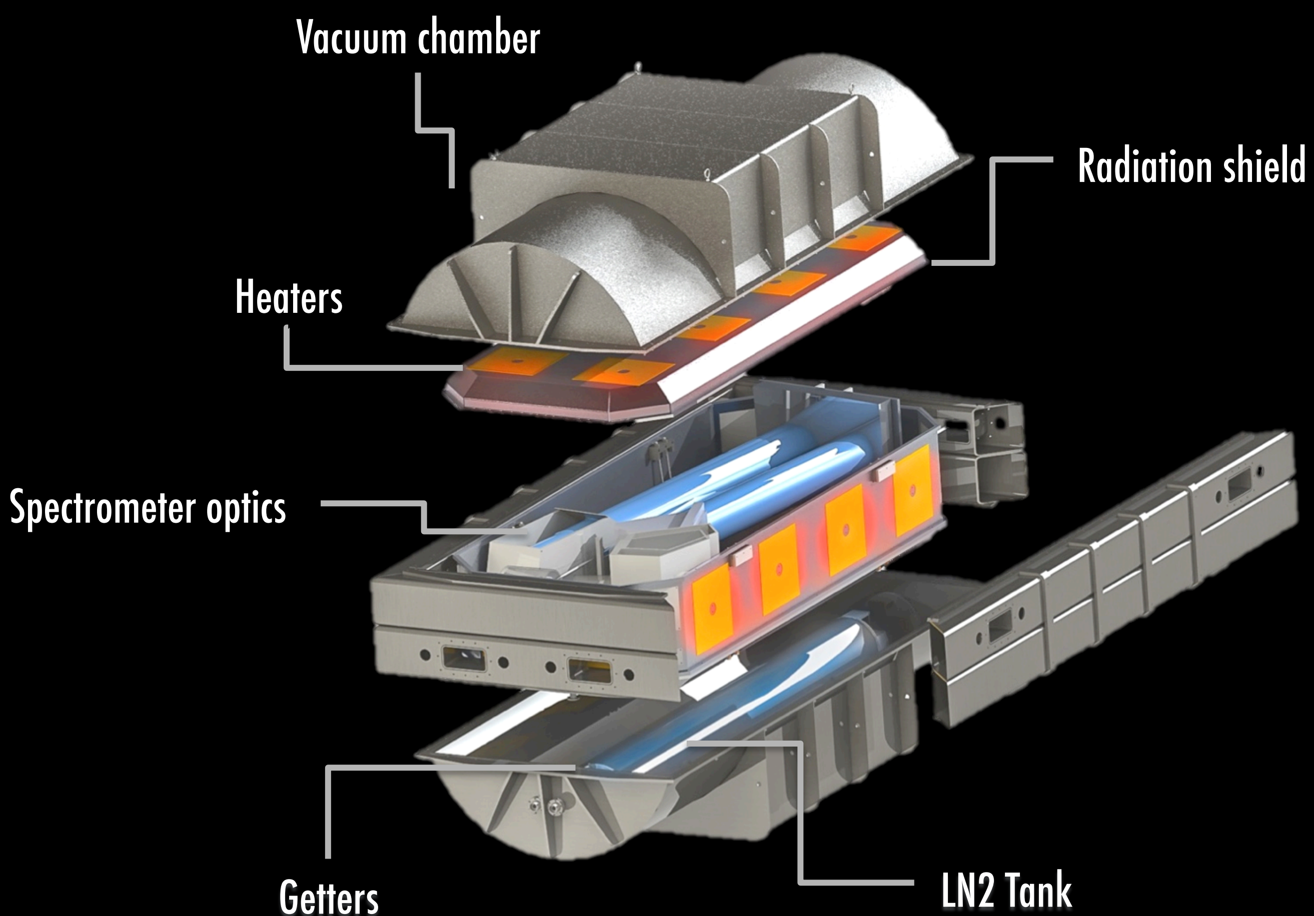
WIYN telescope

- Located @ Kitt Peak in southern Arizona
- 3.5 meter primary mirror
- Partners: Wisconsin, Indiana, NOAO, NSF
- *NN-Explore program announced in 2015 for dedicated exoplanet research*
- **140 nights / year allocated to exoplanet studies**
- **Queue-based observing implemented for NEID GTO program (30 queue nights per year, 5 years)**



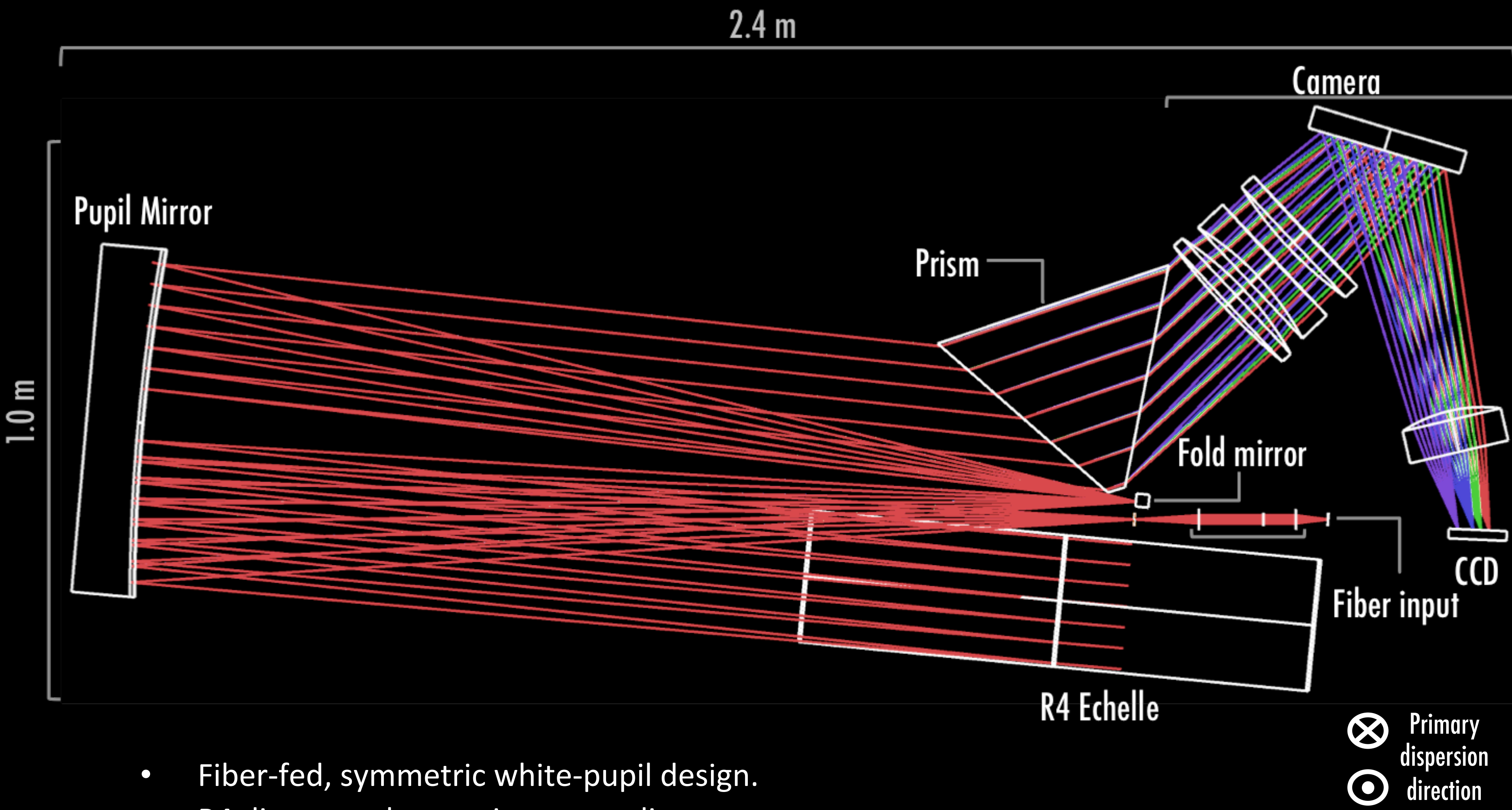
http://www.noao.edu/wiyn/

NEID: the next technological step in Doppler measurement machines



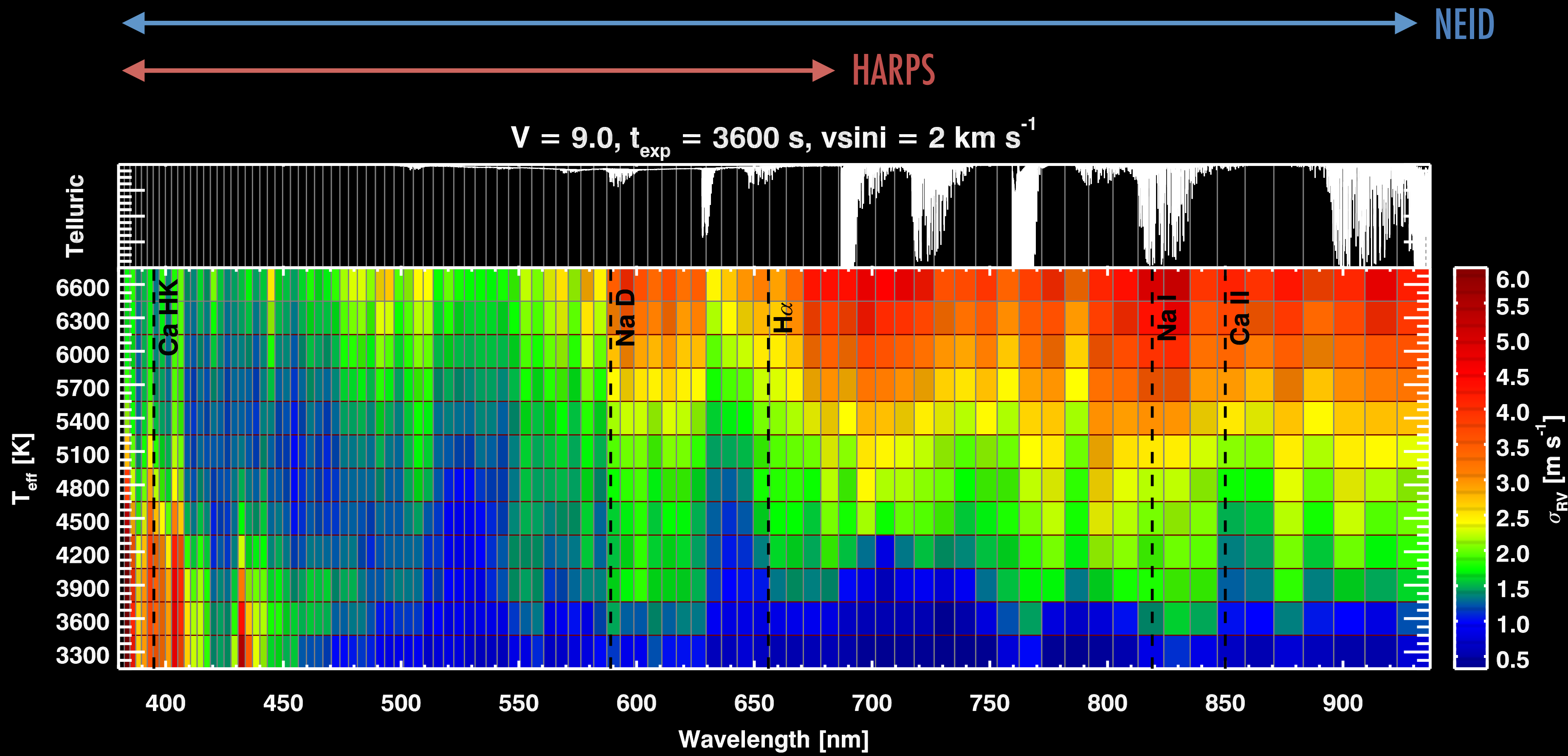
- Covers full optical range (380 – 930 nm)
- *Precision goal is 10 cm s^{-1} (not including star)*
- **Broadband commercial optical frequency comb calibration source**
- **Q3 2018 delivery**

NEID optical layout



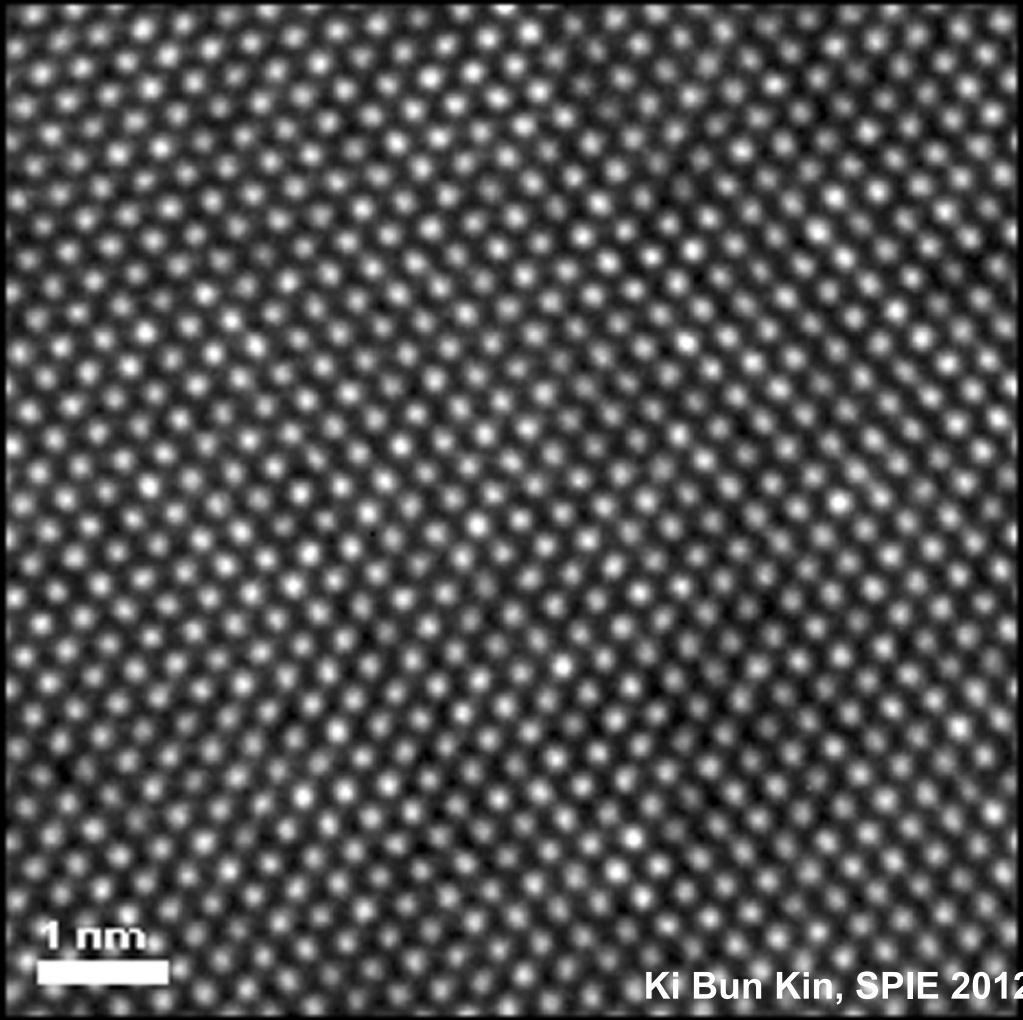
- Fiber-fed, symmetric white-pupil design.
- R4 disperser, large prism cross-disperser
- R = 100,000, 380 – 930 nm coverage
- **9k x 9k e2v CCD, 10 micron pixel pitch (90 x 90 mm)**

Wide spectral grasp is essential



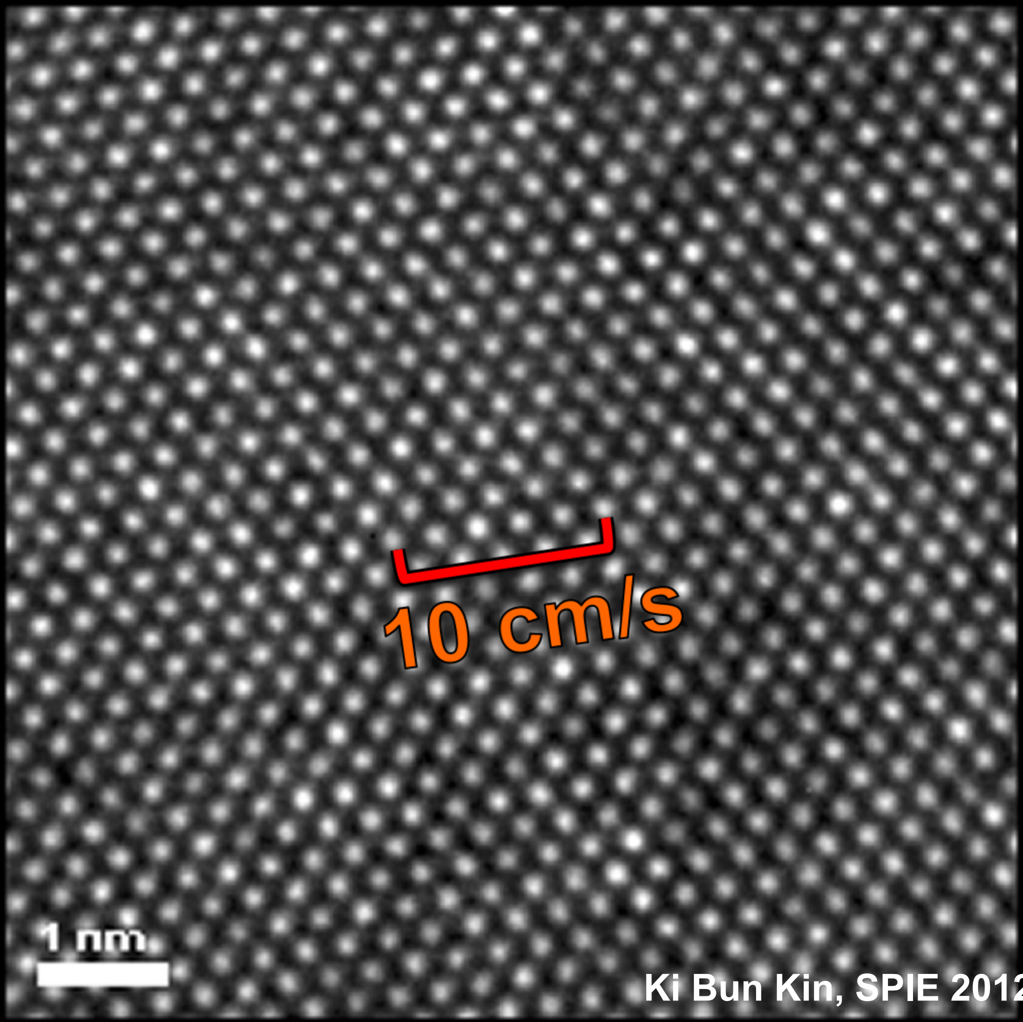
- Wide bandwidth essential for activity indicators
- *Enables study of wide range of spectral types*

What does 10 cm s^{-1} look like?



TEM image of silicon wafer lattice

What does 10 cm s^{-1} look like?

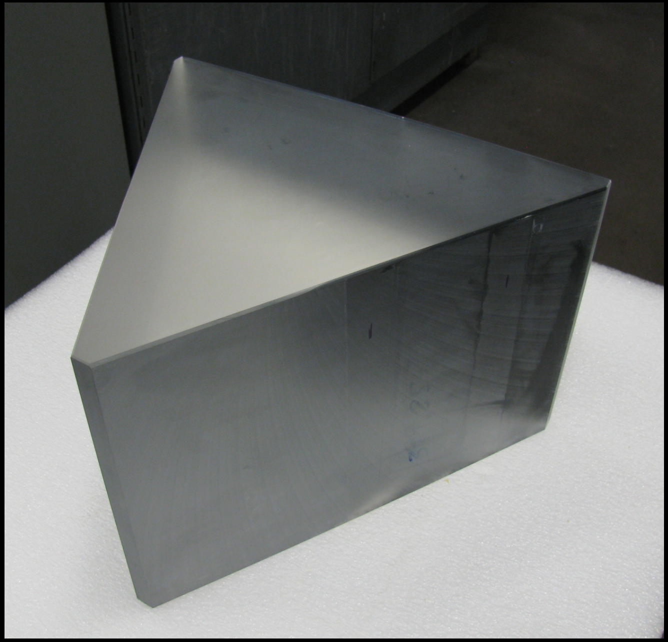


TEM image of silicon wafer lattice

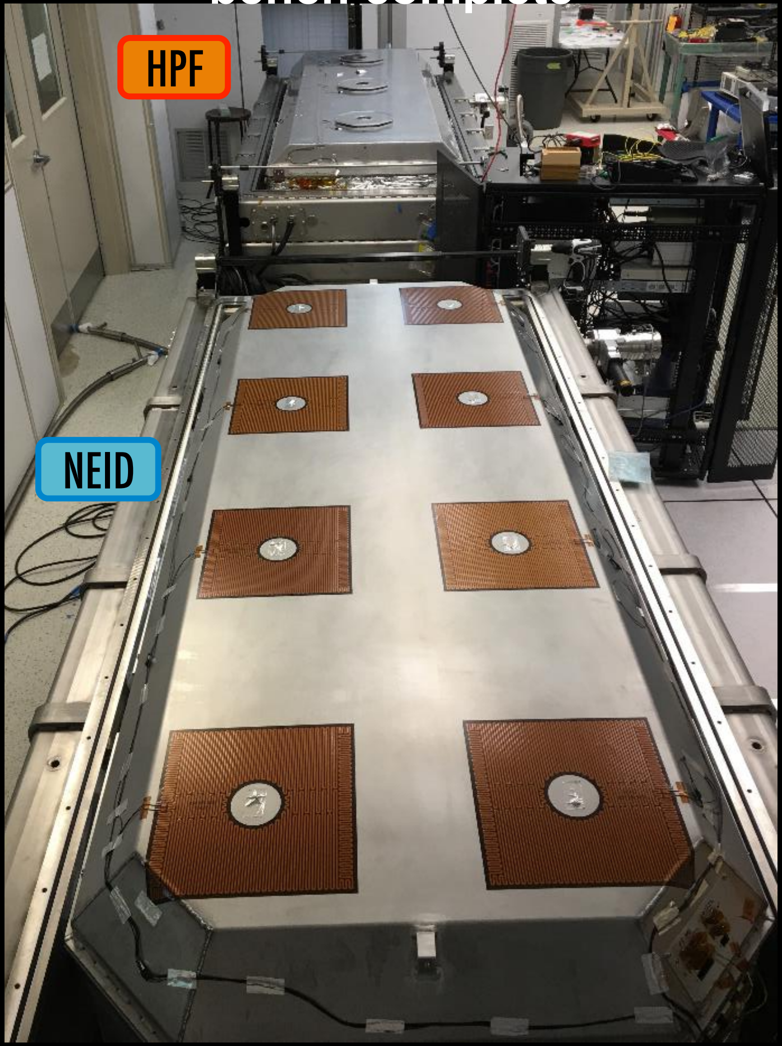
Major component fabrication well underway

Echelle grating complete

Prism being fabricated

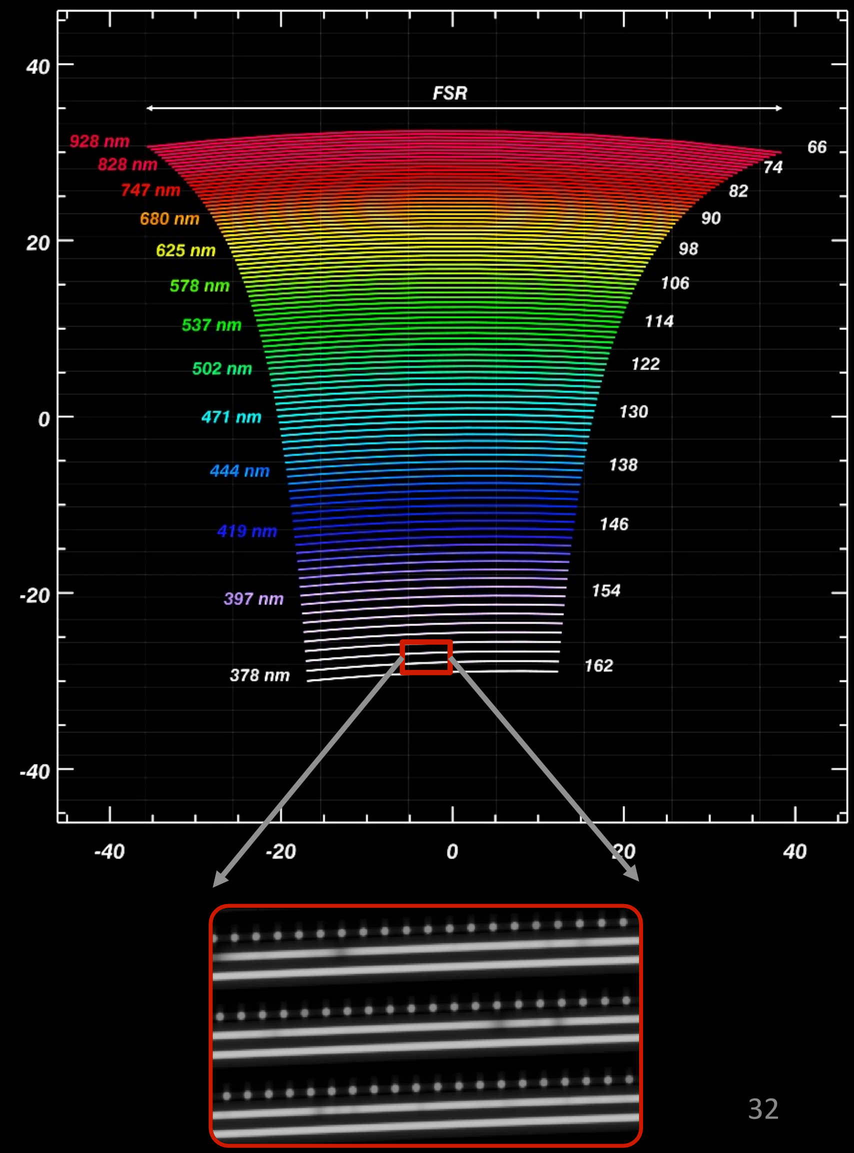


Vacuum chamber, radiation shield, optical bench complete



New technologies to tackle old problems

- Beyond the era where single instrumental error source dominates measurement precision
- NEID will require suite of cutting edge technologies to reach precision goal:
  - **Broadband commercial laser frequency comb calibration source**
  - **Stabilized broadband fabry-perot etalon source** (Halverson+ 2012, Halverson+ 2013, Halverson+ 2014a)
  - **Extremely stable instrument illumination.** (Halverson & Roy+ 2015, Halverson+ 2016a)
  - **New fiber modal noise mitigation techniques** (Halverson+ 2014b, Mahadevan & Halverson+ 2014)
  - **Improved CCD characterization and calibration** (Blake & Halverson+ 2017, Halverson+ 2017 in prep)
  - **Solar contamination mitigation techniques** (Roy & Halverson+ 2017, in prep.)
  - **Novel barycentric correction techniques**
  - …
  - **… n -> ∞**



Performance budgeting is key for estimating measurement precision at these levels

Total NEID instrumental error budget: 27.0 cm s^{-1}

Instrument (uncalibratable): 15.1 cm s^{-1} (30.6%)

Fiber & illumination: 8.7 cm s^{-1}

Calibration source modal noise	2.5 cm s^{-1}
Continuum modal noise	2.5 cm s^{-1}
Near-field scrambling	3.5 cm s^{-1}
Far-field scrambling	5.0 cm s^{-1}
Stray light	5.0 cm s^{-1}
Polarization	2.0 cm s^{-1}

Detector effects: 7.1 cm s^{-1}

Readout thermal change	5.0 cm s^{-1}
Charge transfer inefficiency	5.0 cm s^{-1}

Barycentric correction: 1.7 cm s^{-1}

Algorithms	1.0 cm s^{-1}
Exposure midpoint time	1.0 cm s^{-1}
Coordinates and proper motion	1.0 cm s^{-1}

Reduction pipeline: 10 cm s^{-1}

Software algorithms	10 cm s^{-1}

25%

Instrument (calibratable): 11.2 cm s^{-1} (1.1%)

Thermo-mechanical: 7.8 cm s^{-1}

Thermal stability (grating)	3.5 cm s^{-1}
Thermal stability (cross-disp.)	3.0 cm s^{-1}
Thermal stability (bench)	3.0 cm s^{-1}
Vibrational stability	2.0 cm s^{-1}
Pressure stability	<0.1 cm s^{-1}
LN2 fill transient	1.0 cm s^{-1}
Zerodur phase change	5.0 cm s^{-1}

Detector effects: 8.1 cm s^{-1}

Pixel inhomogeneities	1.0 cm s^{-1}
Electronics noise	1.0 cm s^{-1}
Stitching error	3.0 cm s^{-1}
CCD thermal expansion	2.0 cm s^{-1}
Readout thermal change	5.0 cm s^{-1}
Charge transfer inefficiency	5.0 cm s^{-1}

Calibration source (uncalibratable): 11.5 cm s^{-1} (18.7%)

Calibration accuracy: 5.7 cm s^{-1}

Stability	4.0 cm s^{-1}
Photon noise	4.0 cm s^{-1}

External errors (uncalibratable): 18.7 cm s^{-1} (49.6%)

Calibration process: 10 cm s^{-1}

Software algorithms	10 cm s^{-1}

Telescope: 12.2 cm s^{-1}

Guiding	scrambling
ADC	6.9 cm s^{-1}
Focus	5.0 cm s^{-1}
Windshake	8.0 cm s^{-1}

Atmospheric effects: 14.1 cm s^{-1}

Micro-telluric contamination	10 cm s^{-1}
Sky fiber subtraction	10 cm s^{-1}

- **HPF will be first NIR RV planet hunter on 10 m telescope (Q3 2017)**
- Large aperture gives unparalleled access to wide array of nearby M-dwarfs
- Valuable instrument for following up TESS M-dwarf targets, down selection for JWST
- Will utilize a suite of new technologies to probe the M-dwarf planet discovery space:
  - Highly stabilized optical train
  - Optical frequency comb calibration source
  - Unique optical fiber delivery system

- **NEID aims to be next technological step in Doppler spectroscopy for finding Earth-twins**
- Gives US community unprecedented capability for planet detection, follow-up of interesting targets discovered by TESS / K2, direction for JWST / WFIRST-AFTA
  - Queue-based observing, combined with extremely stable spectrometer.
  - Builds off technologies developed for HPF
  - Modeling of instrumental errors at the cm/s level is key for understanding systematics, charting path towards 10 cm s^{-1}